CO_2 Utilization beyond EOR

Resources for the Future
May 24, 2017

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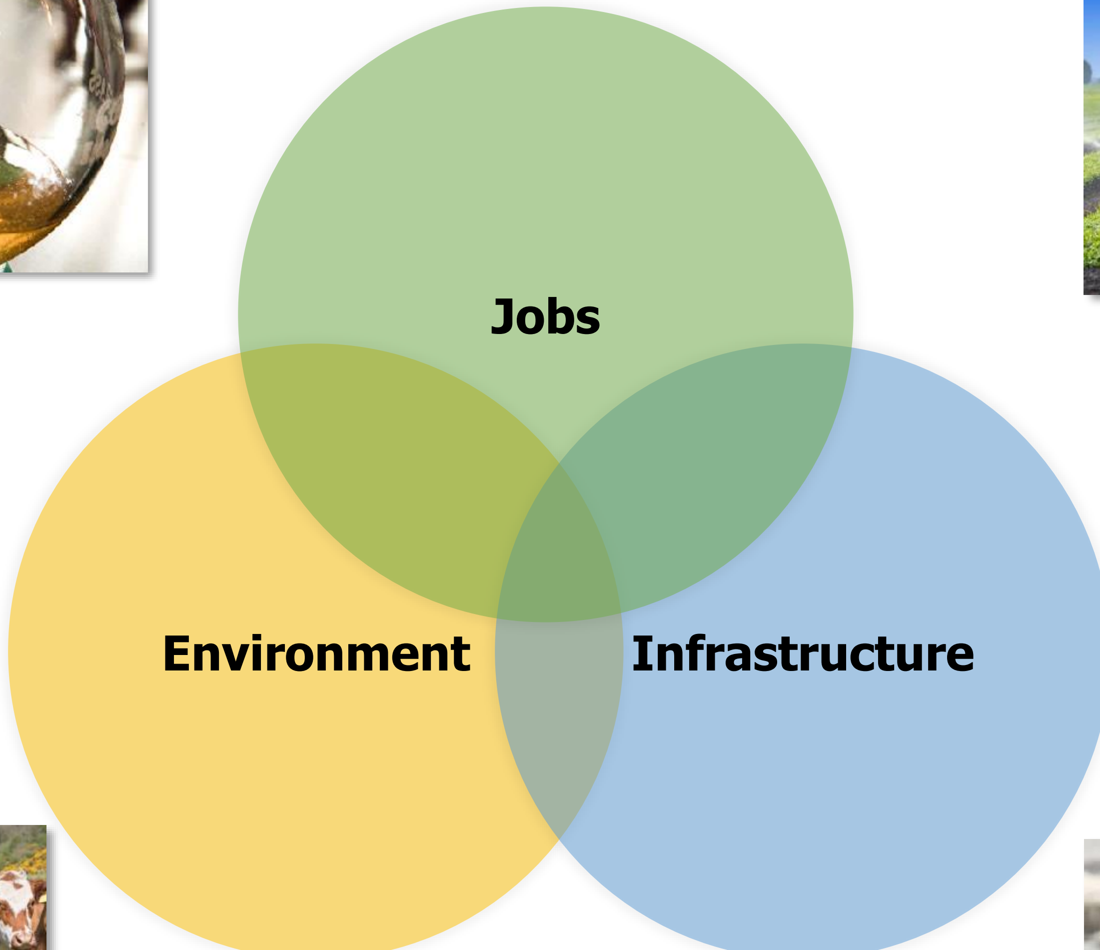
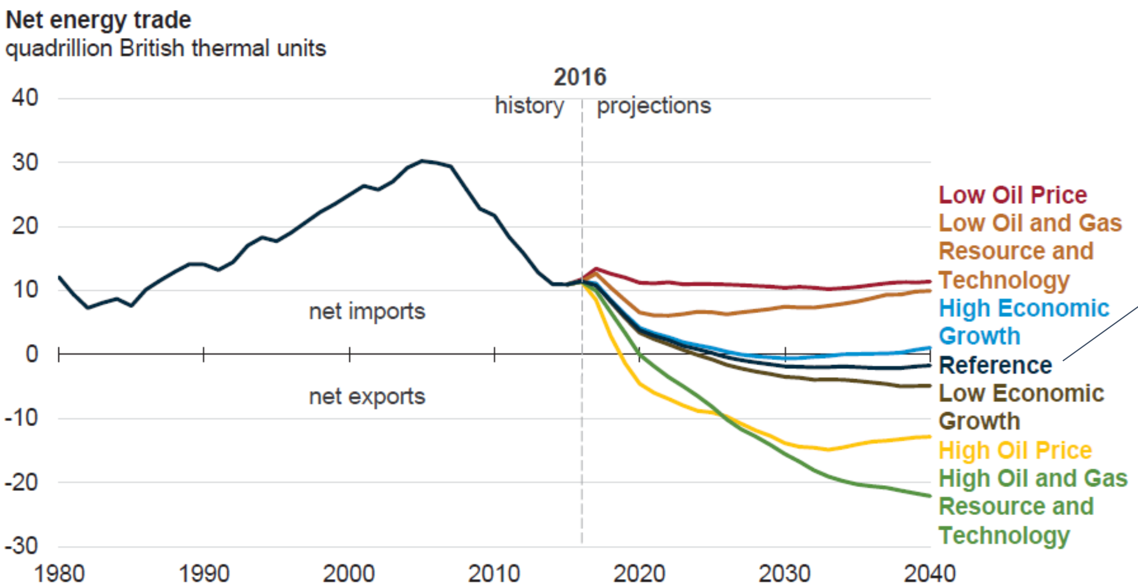
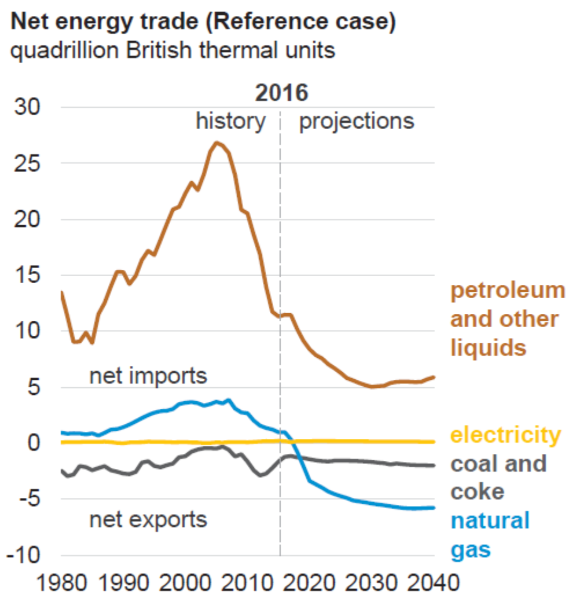
There are many reasons to advance CO_2 Utilization technologies



Abundant energy

U.S. is projected to become a net energy exporter in most AEO2017 cases. *EIA Annual Energy Outlook 2017.*



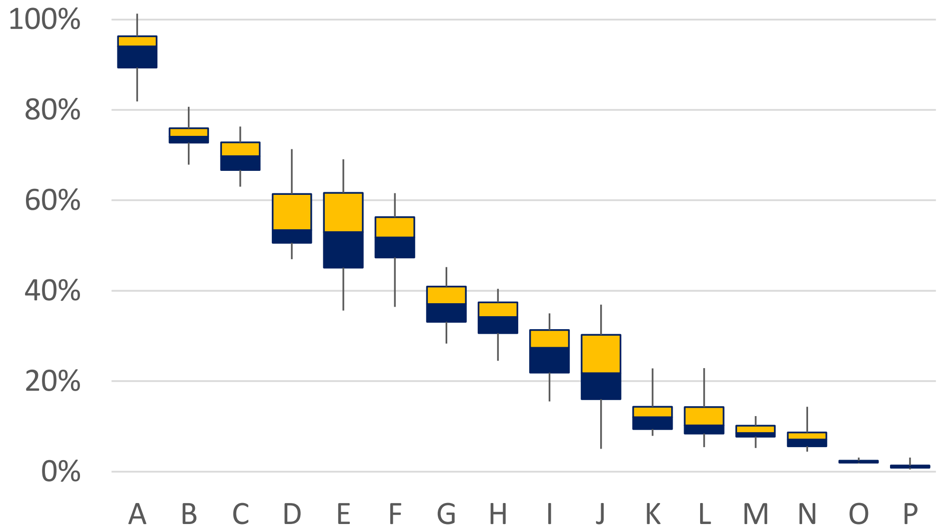


All resources but electricity may become net exports.

Can efficient U.S. electricity be exported by embedding into salable products derived from CO_2?

Abundant electric capacity

Monthly Capacity Factors for Utility Scale Electricity Generators 2015-16. *EIA, Electric Power Monthly (Table 6.7, April 2017).*



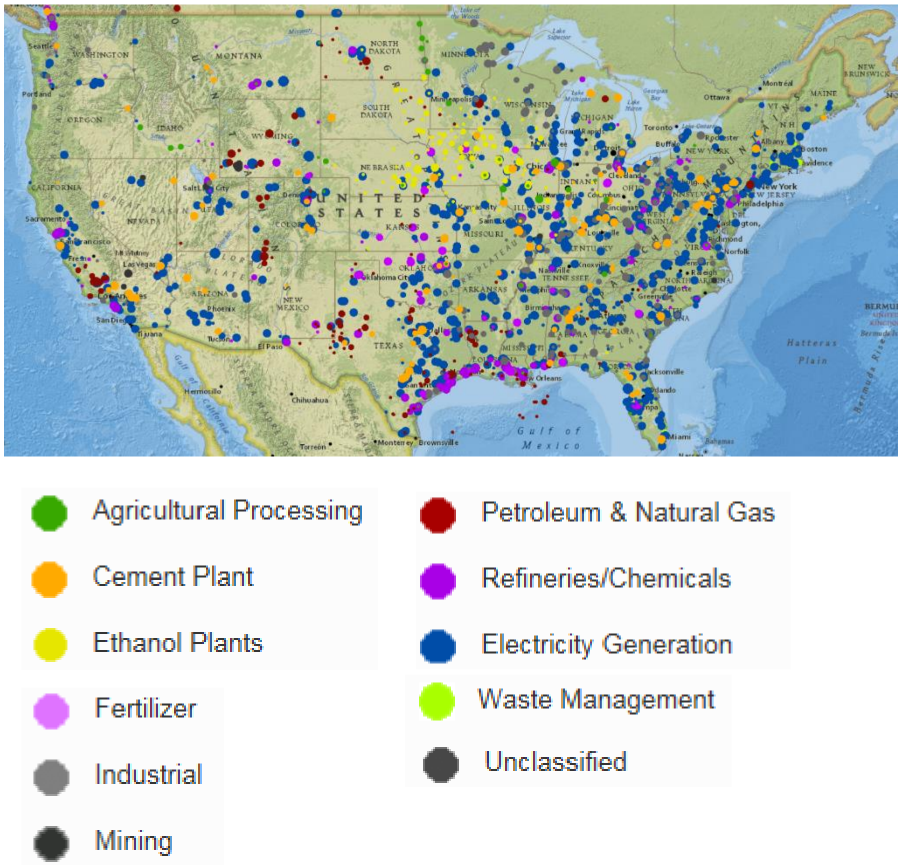
(A) nuclear
(B) geothermal
(C) landfill gas and muni solid
(D) natural gas fired combined cycle
(E) coal
(F) other biomass incl. wood
(G) conv. hydropower
(H) wind
(I) solar PV
(J) solar thermal
(K) steam turbine, gas
(L) steam turbine, petroleum
(M) internal combustion engine, gas
(N) combustion turbine, gas
(O) internal combustion engine, petroleum
(P) combustion turbine, petroleum

U.S. infrastructure has excess generation capacity to the extent that even new natural gas plants cannot become economical in some areas (e.g. *Hughes vs. Talen Energy Marketing*).

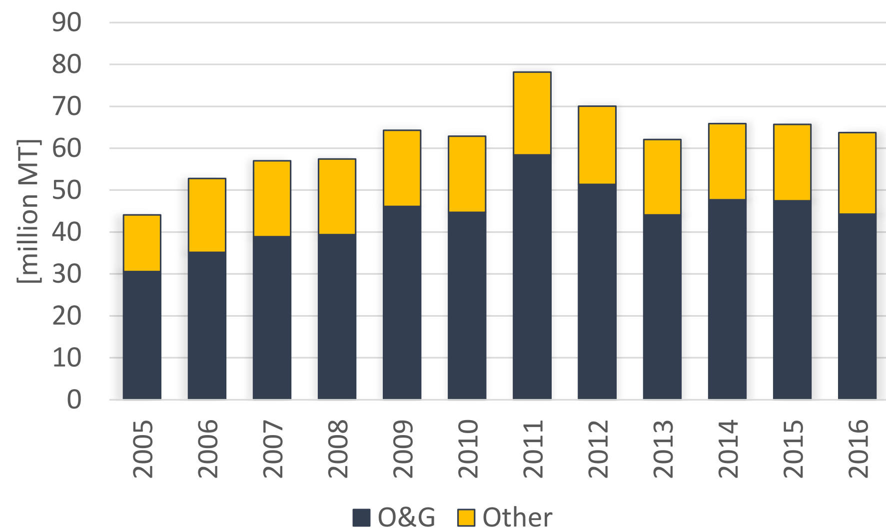
Can the existing fleet be repurposed to service an export economy?

U.S. CO_2 sources and use

U.S. CO_2 Sources. *Many point sources provide high to low purity CO_2. The total CO_2 supply was 5,414 million MT in 2015. Source: NatCarb.*

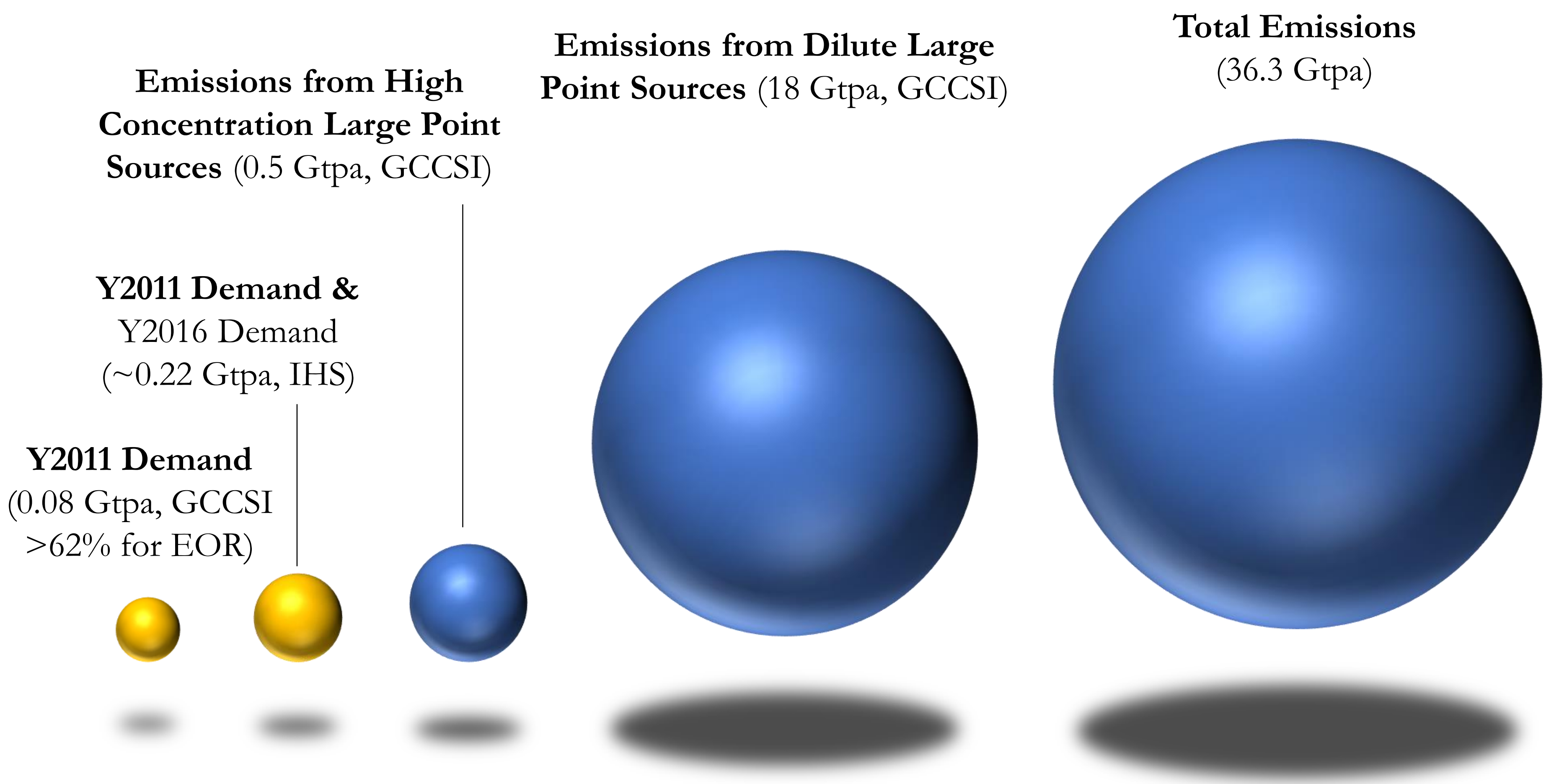


U.S. CO_2 Consumption. *The majority of CO_2 is used in the Oil & Gas sector, mostly by pipeline. Adapted from IHS Markit sources.*



NETL, NatCarb database: http://natcarb.netl.doe.gov
Bala Suresh, IHS Markit, "Global Market for Carbon Dioxide", presented at 8th Carbon Dioxide Utilization Summit (Feb 2017)

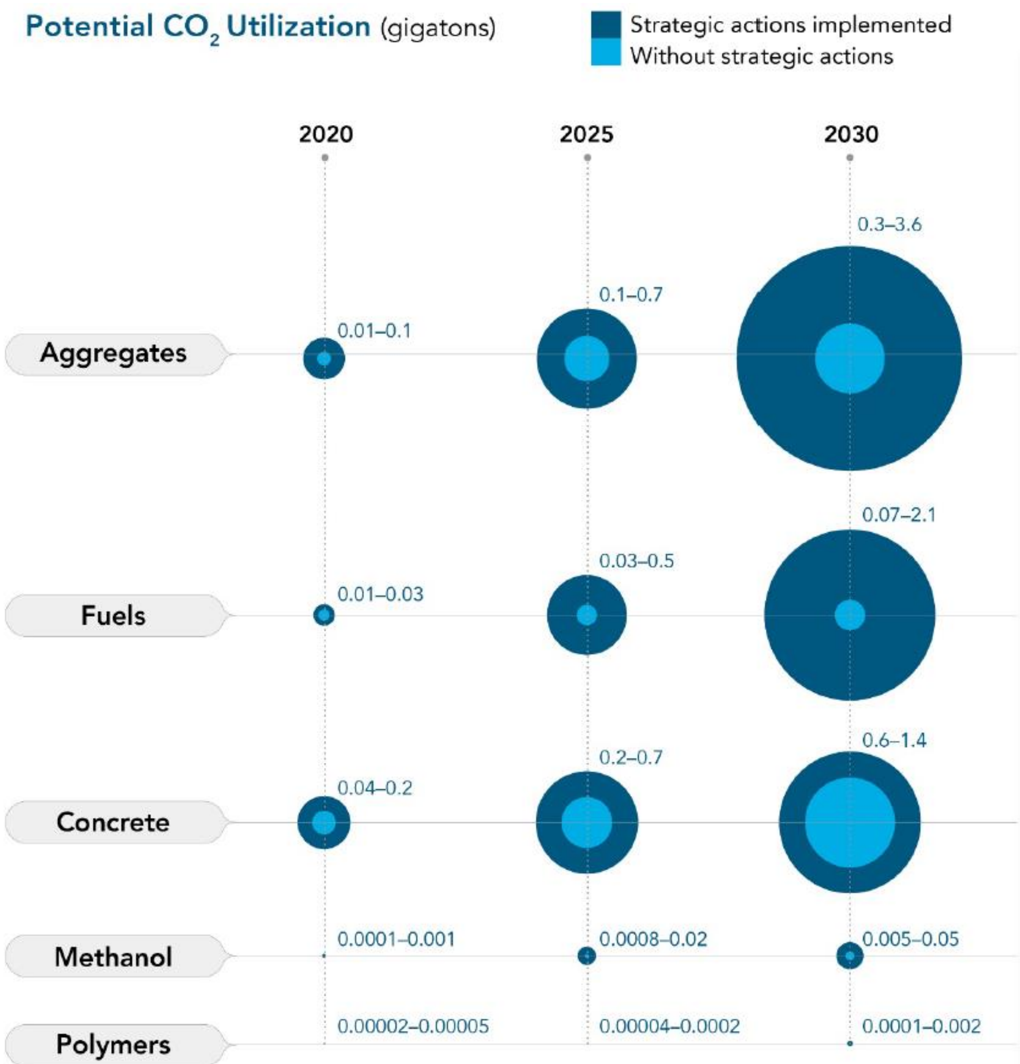
Global CO_2 demand and supply



GCCSI, Parsons Brinckerhoff, "Accelerating the Uptake of CCS: industrial use of carbon dioxide" (Dec 2011);
Bala Suresh, IHS Markit, "Global Market for Carbon Dioxide", presented at 8th Carbon Dioxide Utilization Summit (Feb 2017)

An upper bound for CO_2 markets?

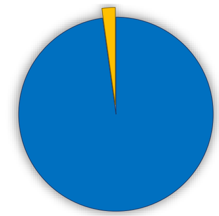
Global CO_2 Initiative provides the following perspective,

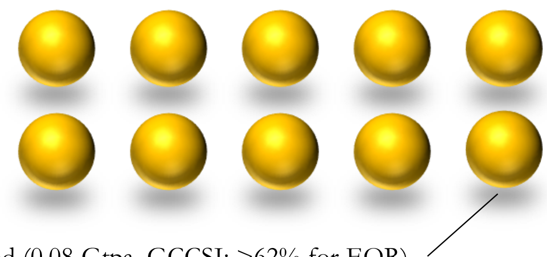


- "CO_2U has the potential to utilize 7 billion metric tons of CO_2 per year by 2030"
- Revenue potential estimated at >$800 billion by 2030
- "This is an upper bound estimate, assuming zero carbon energy is used in all production processes"
- "To the extent that climate benefits are a goal of those promoting CO_2U products, life cycle analysis (LCA) is essential."
- "Considerable work is needed to standardize life cycle analysis methodologies for CO_2U."

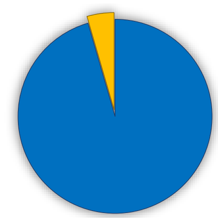
Global CO2 Initiative, "Carbon Dioxide Utilization (CO_2U)--ICEF Roadmap 1.0" (Nov 2016)

"If CO_2 was to be used as the source of all carbon in the global annual production of plastics (311 million tonnes (MT) per year in 2014), it would consume about 0.8 $GtCO_2$ per year."





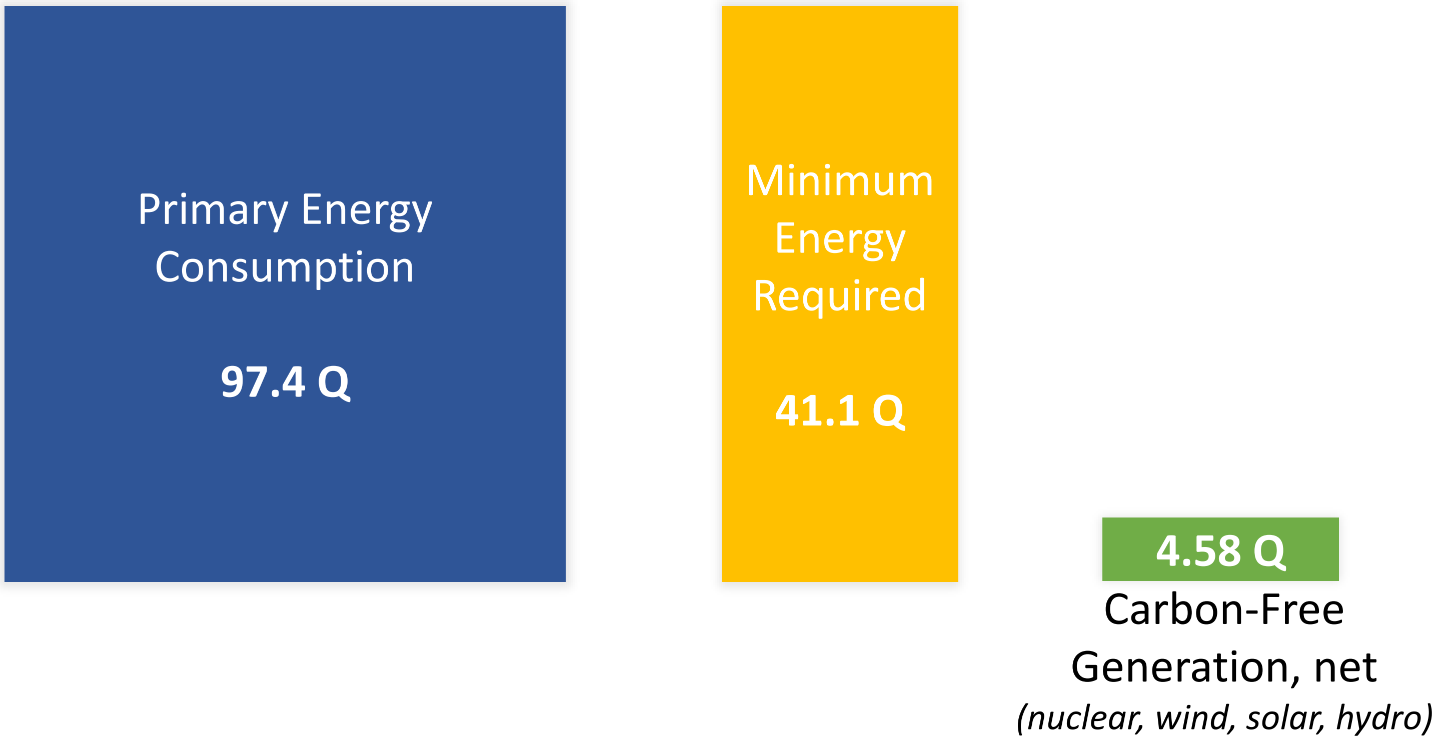
"By 2030, the annual global plastic production is expected to rise to 700 MT, which would require roughly 490 MtC/yr or about 1.8 $GtCO_2$/yr."



Final report of the Secretary of Energy Advisory Board (SEAB) Task Force on CO2 Utilization
https://energy.gov/seab/downloads/final-report-task-force-co2-utilization

Limitations of Existing Renewable and Nuclear Energy

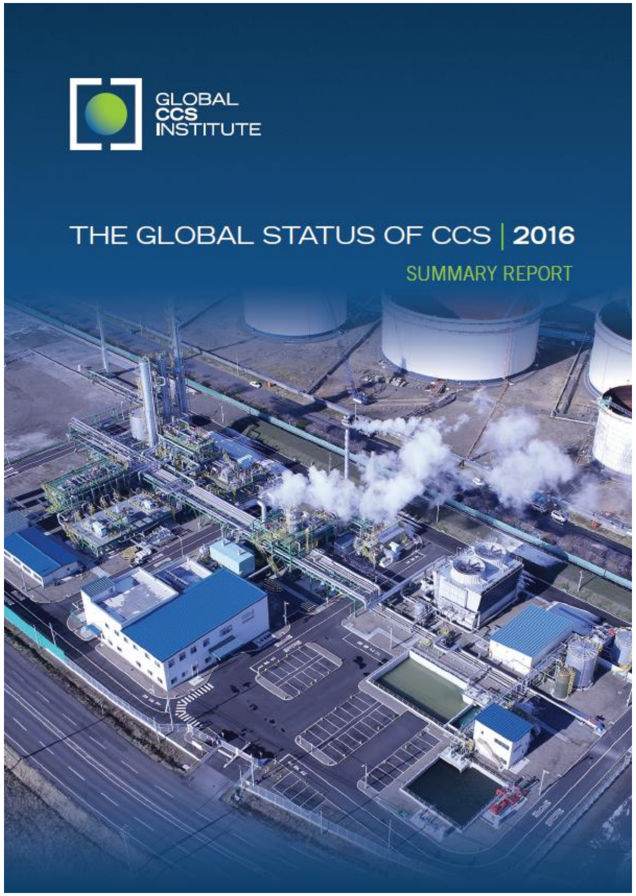
If CO_2 was converted into barrel of oil equivalents, and so used to replace the barrels of oil consumed in the US in Y2015,



U.S. renewable and nuclear generation would need expand by a minimum of 897% in order to displace crude oil consumption.

Comparison attributed to Final report of the Secretary of Energy Advisory Board (SEAB) Task Force on CO2 Utilization
https://energy.gov/seab/downloads/final-report-task-force-co2-utilization

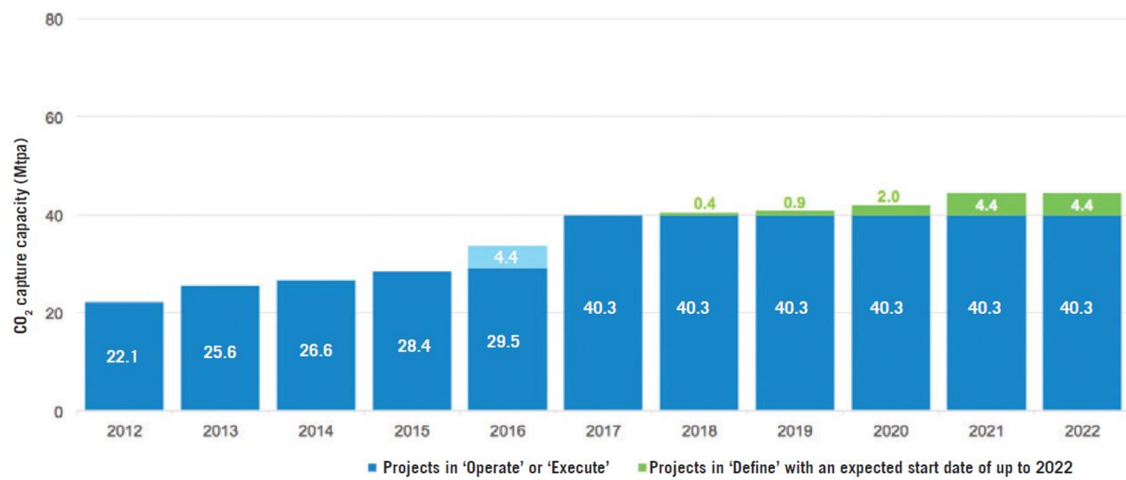
Building confidence in CCS



17 large scale projects in "Operate" stage

- 14 EOR + 3 geological storage
- 2 power generation (EOR)

+ 5 currently active in "Execute" stage
(i.e. beyond the final investment decision)



Can non-EOR CO_2 utilization drive a project into the "Operate" stage?

Making CCS look cheaper: high-purity CO_2 sources

High-purity gas streams are easier to separate - makes CCS appear cheaper

Source	Cost Estimate [USD/tCO_2]
LNG plant	9
Offshore NGP (deep water)	31
Offshore NGP (shallow water)	18-21
Onshore NGP	16-19
Ammonia	4-47
Hydrogen	15
Coal-to-Liquids	<25

More than half of the 17 large-scale projects in "Operate" stage use high purity sources:

- 8 Natural Gas Processing (NGP)
- 2 Ammonia production (fertilizer)
- 2 Hydrogen production

EOR & geological storage only

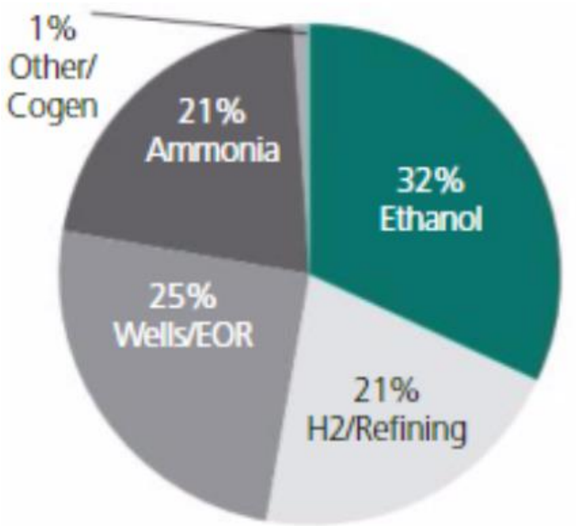
~31.2 Mtpa CO_2 capacity globally

~21.9 Mtpa CO_2 capacity in the US

SOURCE: P. Zakkour, G. Cook, "CCS Roadmap for Industry: High-purity CO2 sources", Carbon Counts report (2010)

Yet >10 Mtpa merchant CO_2 market (non-EOR) in U.S.

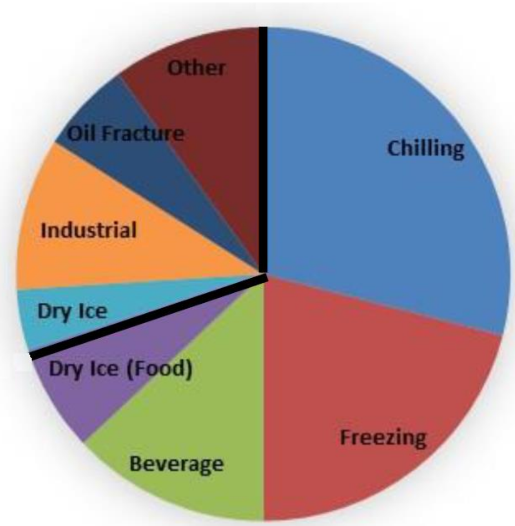
Crude CO_2 sources for the U.S. Merchant Market 2015. *Nameplate capacity ~12.9 Mtpa; capacity factor 86%.*



SOURCE: Maura D. Garvey, published in CryoGas magazine (May 2016)

There is plenty of carbon capture from high-purity CO_2 sources; very little storage.

Merchant demand by End-Use, *US: 10 Mtpa (2016). Food industry drives ~70% of market.*



Adapted from Maura Garvey (presentation Mar 2017); original source JR Campbell & Associates

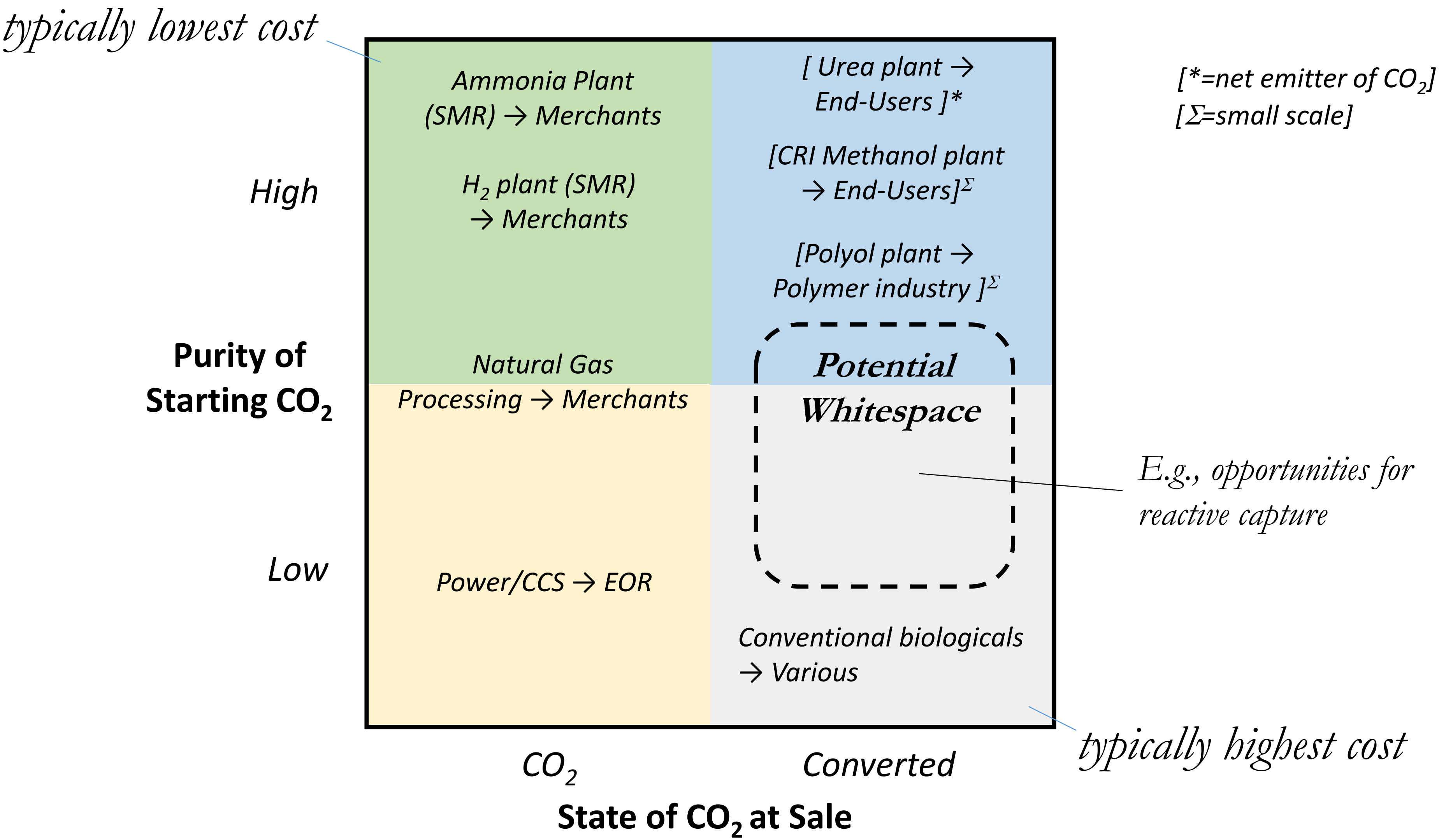
The majority of CO_2 remains unreacted after being used in the merchant markets.

These commercial approaches rely on carbon capture and are sufficiently addressed by the private sector. Most emit CO_2 and operate on a small scale.

Case Study: exporting excess electricity from Iceland

Electricity is used to convert CO_2 from a natural source (at $7/tonne) to a transportation fuel for a Swedish ferry operator, Stena.

Review and potential whitespace



Infrastructure – concepts that may improve resilience

U.S. farmers expect volatile weather to be the norm. *WSJ, May 15, 2017.*


R6 | Monday, May 15, 2017 THE WALL STREET JOURNAL.

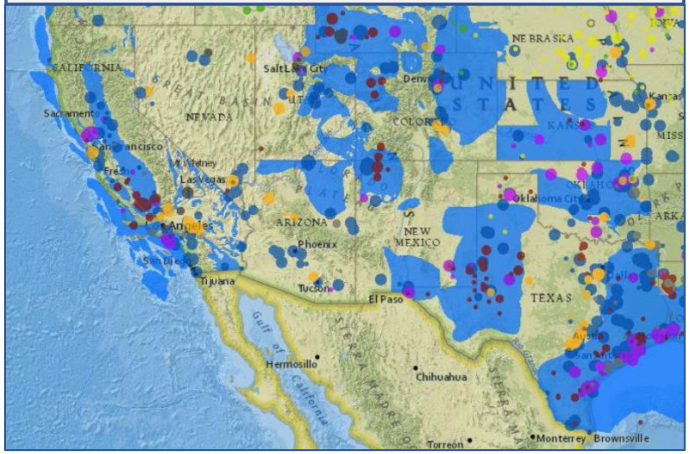
JOURNAL REPORT | AGRICULTURE

Farmers Scramble to Adapt To Volatile Weather

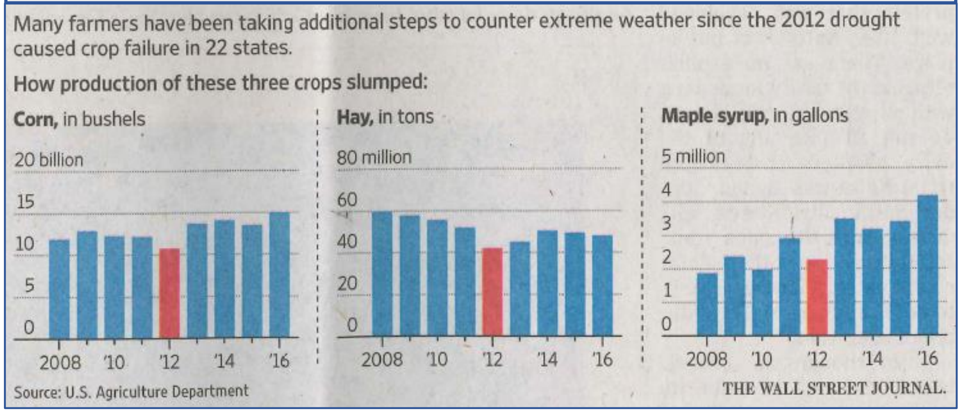
Among the tools: no-till farming, misting and faster planting

No-till farming leaves stubble from a previous harvest in the ground for new planting, to protect soil and seeds from erosion and drought.

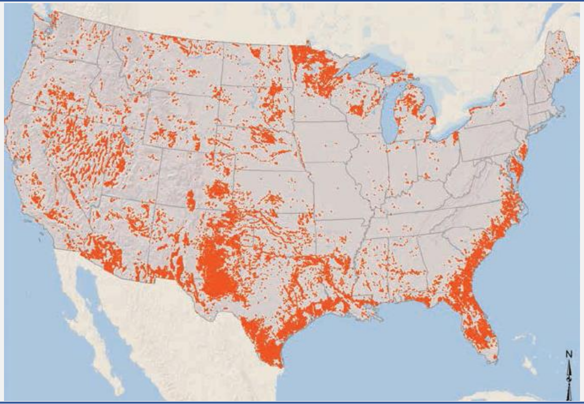
Saline formations and CO_2 point sources. *NETL, NatCarb 2015.*



Exemplary variation in crop production. *WSJ, May 15, 2017; USDA data.*



Potentially suitable lands for algae facilities. *EERE, 2016 Billion Ton Report*



CO_2-enhanced water recovery & CO_2-enhanced food production (e.g. algae for animal feed) may supplement current sources in times of need.

Aggregates *and their qualities are essential to well functioning and durable concrete structures. They can be made by mineralizing CO_2.*

IMAGES: Portland Cement Association

Key Challenges*. Forming stable mineral carbonates is

- highly process-dependent and thus has the potential to emit more CO_2 than is sequestered
- may be constrained to a limited scale due to the supply of make up materials

Key trend: Urbanization

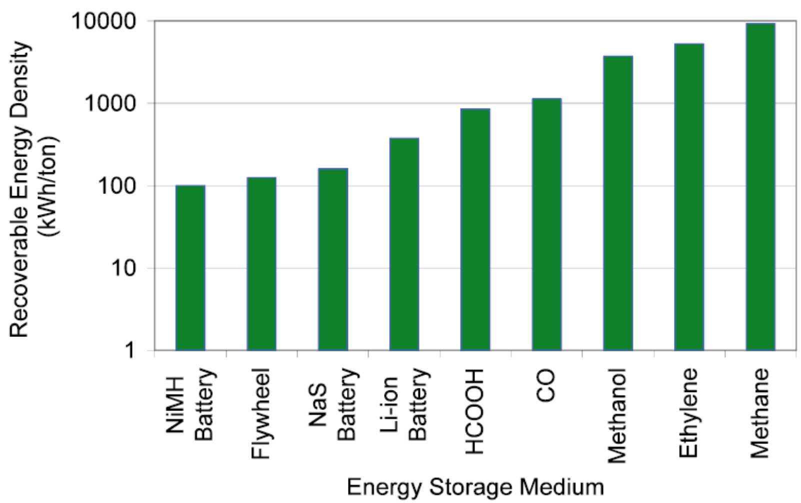
By 2030, 60% of the population will live in an urban world. Less developed regions will add more than 1 billion people to urban centers.

DATA: UN DESA
IMAGE: Erla Zwingle (National Geographic)

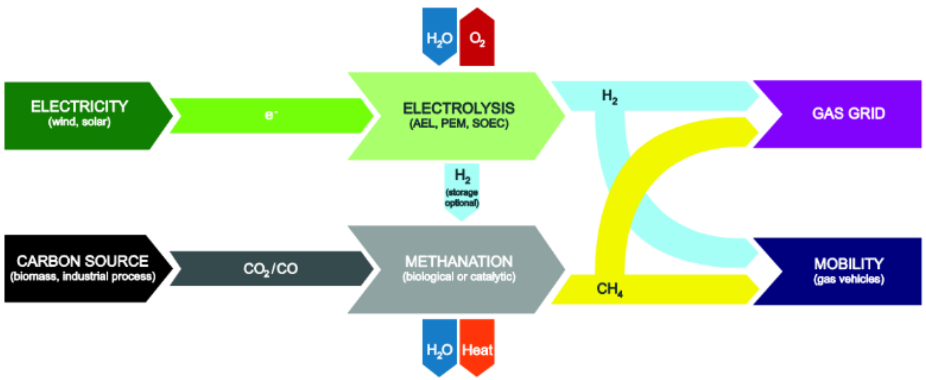
* **Newall**, P. S., Clarke, S.J., Haywood, H.M., Scholes, H., Clarke, N.R ., King, P.A., Barley, R.W., 2000: *CO2 storage as carbonate minerals*, report PH3/17 for IEA Greenhouse Gas R&D Programme, CSMA Consultants Ltd, Cornwall, UK
Erla Zwingle, "Cities -- Challenges for Humanity", National Geographic Magazine, November 2002
UN Department of Economic and Social Affairs, Urban and Rural Areas wallchart 2014.

Energy storage

Energy Density. *Products from CO_2 conversion have more energy density than other storage solutions. Source: DNV 2011.*



Power to Gas. *Excess energy can be stored as CH_4 in natural gas pipelines, at least in theory. Source: M Gotz et al.*



The value of deferred investment in transmission and distribution (T&D) is the likely driver for deployment of such technologies instead of arbitrage revenues (at least in current U.S. power markets). Urbanization will continue to be a key trend placing stress on T&D.

DNV, "Carbon Dioxide Utilization: Electrochemical Conversion of CO_2 – Opportunities and Challenges", position paper 07 (2011).
M Gotz, J Lefebvre, F Mors, AM Koch, F Graf, S Bajohr, R Reimert, T Kolb, " Renewable Power-to-Gas: a technological and economic review", Renewable Energy 85 (2016) 1371.

Carbon - the backbone of advanced economies

Advanced Polymers

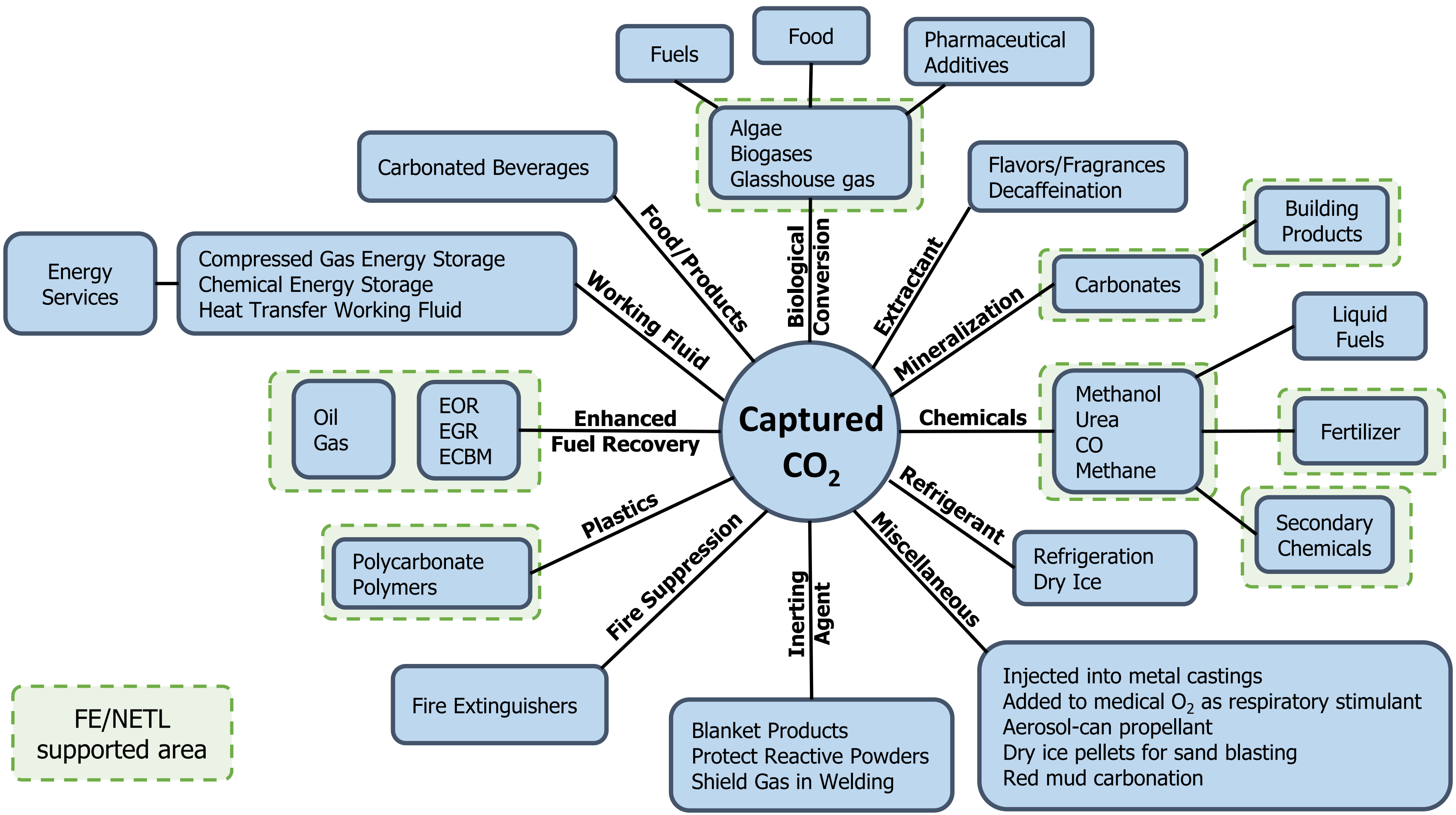
https://i2.wp.com/buildersontario.com/wp-content/uploads/2015/01/spray-foam-

Advanced Materials

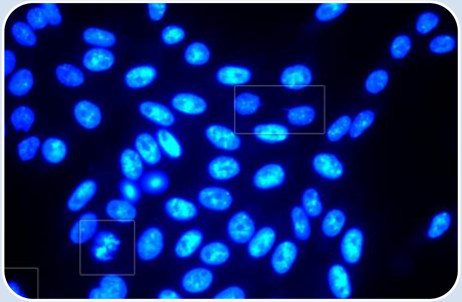
Chemicals and Fuels

CREDITS: DOE Big Ideas Carbon Team comprising national lab colleagues

Sample of Marketable Products and Services derived from CO_2 Use

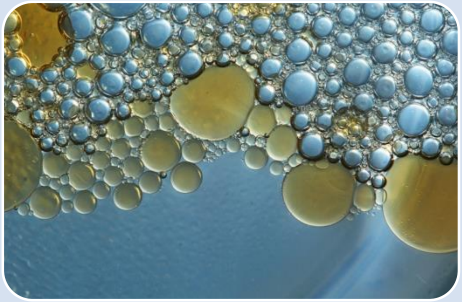


$5.9 million to advance novel CO_2 utilization strategies



Biological based concepts

Mineralization based concepts

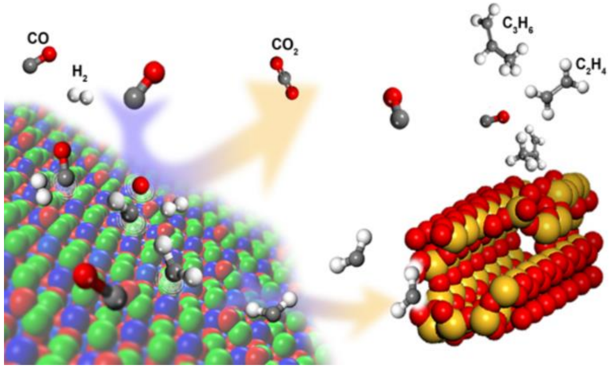


Novel physical and chemical processes

OBJECTIVE: to support efforts to develop technologies that utilize CO_2 from coal-fired power plants as a reactant to produce useful products without generating additional CO_2 or greenhouse gas emissions validated via a product Life Cycle Analysis.

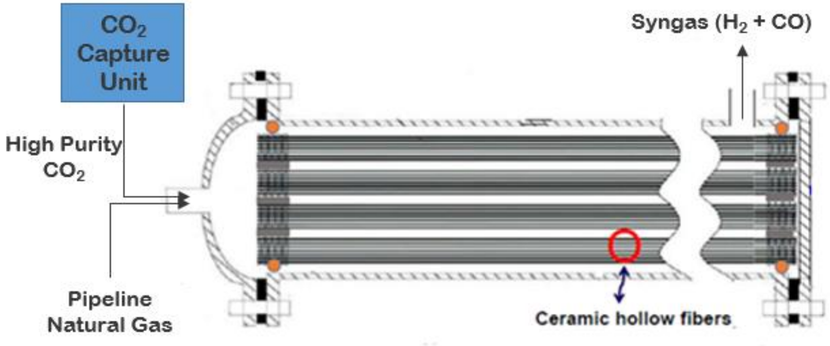
$5.9 million to advance novel CO_2 utilization strategies

CO_2 to light olefins *via a low temperature process using nano-engineered catalysts. [Southern Research Institute]*

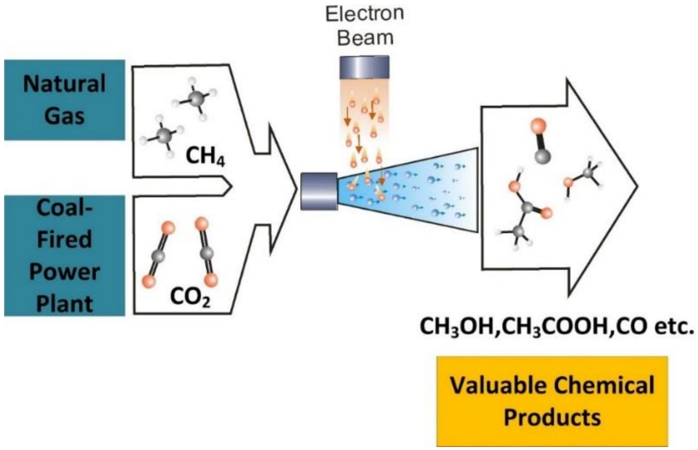


CO_2 to Bioplastics, *beneficial re-use of carbon emissions using microalgae. Image: pilot-scale cyclic flow photobioreactor at Duke's East Bend Station [U. Kentucky]*

Dry reforming *by nano-engineered hollow-fiber supported catalysts in a modular reactor for syngas production. [Gas Technology Institute]*

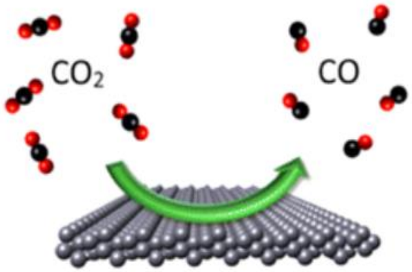


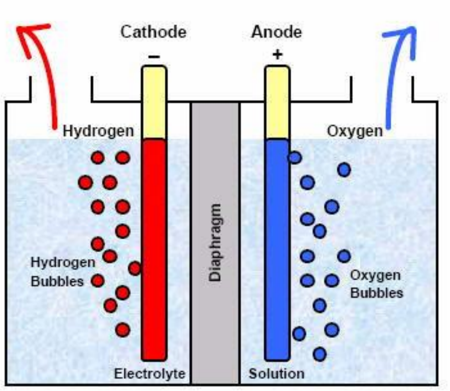
Direct Electron Beam Synthesis *for highly selective conversion of CO_2 [Gas Technology Institute]*



$5.9 million to advance novel CO_2 utilization strategies

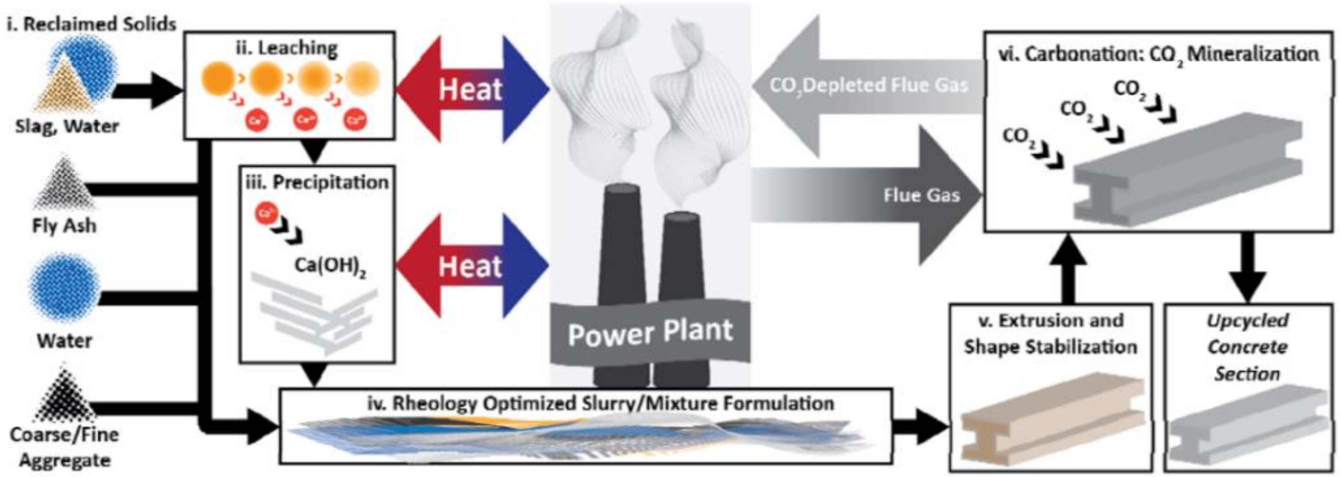
CO_2 to Alcohols, *electrochemical conversion to liquid C2/C3 alcohols using nanostructured catalysts [U. Delaware]*





CO_2 to Fuel, *mixed-oxide sorbent-based, thermo-catalytic process to convert CO_2 to syngas [TDA Research]*

"CO_2-negative" construction materials *via industrial waste re-processing and power plant heat integration. [UCLA]*

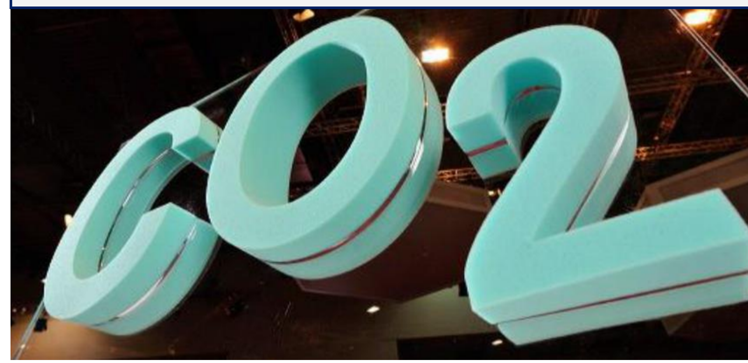


Novomer, Covestro

Ford tests foams based on CO_2.
Materials partially consist of CO_2-based polyols; considered for use as insulation.

NOVOMER

Covestro inaugurates production facility for foams with 20wt% CO_2.
Plant capacity of 5,000 tons/year.



BAYER → covestro

Novomer received $20.4 million in ARRA funding from DOE/FE + had lower TRL support from DOE/AMO and NSF.

Thank You

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