ENERGY GAME CHANGERS

September 18, 2018

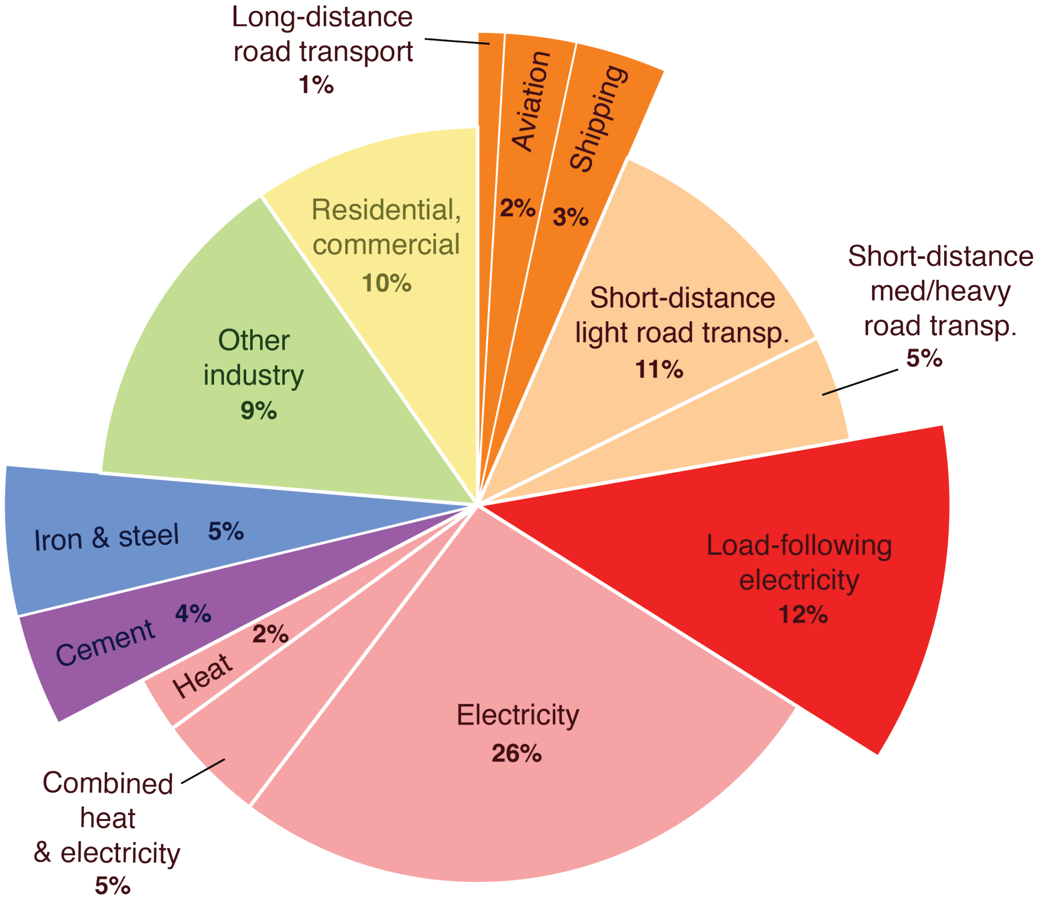
Washington, DC

POWERING US INDUSTRY OF THE FUTURE

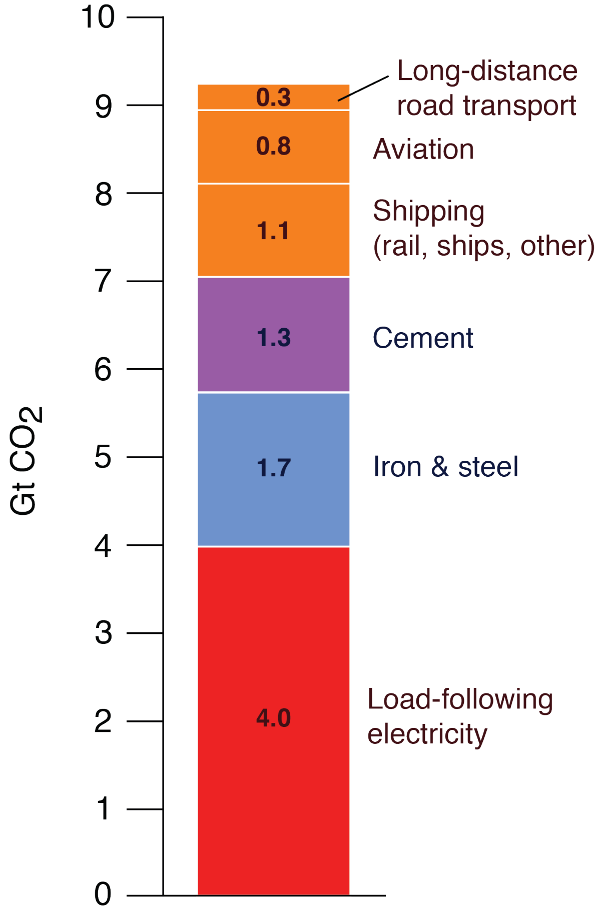
Jeremy Carl (Hoover/Stanford) - Moderator
Sally Benson (Stanford) – Carbon Capture, Utilization & Sequestration
Yogesh Surendranath (MIT) – Electrochemical Manufacturing
Thomas Jaramillo (Stanford) – Fuels
Craig Blue (Oak Ridge National Lab.) – 3-D Printing

Carbon capture, use, and sequestration

Difficult-to-Eliminate CO_2 Emissions Require CO_2 Capture and Sequestration



A Global fossil fuel & industry emissions, 2014 (33.9 Gt CO_2)



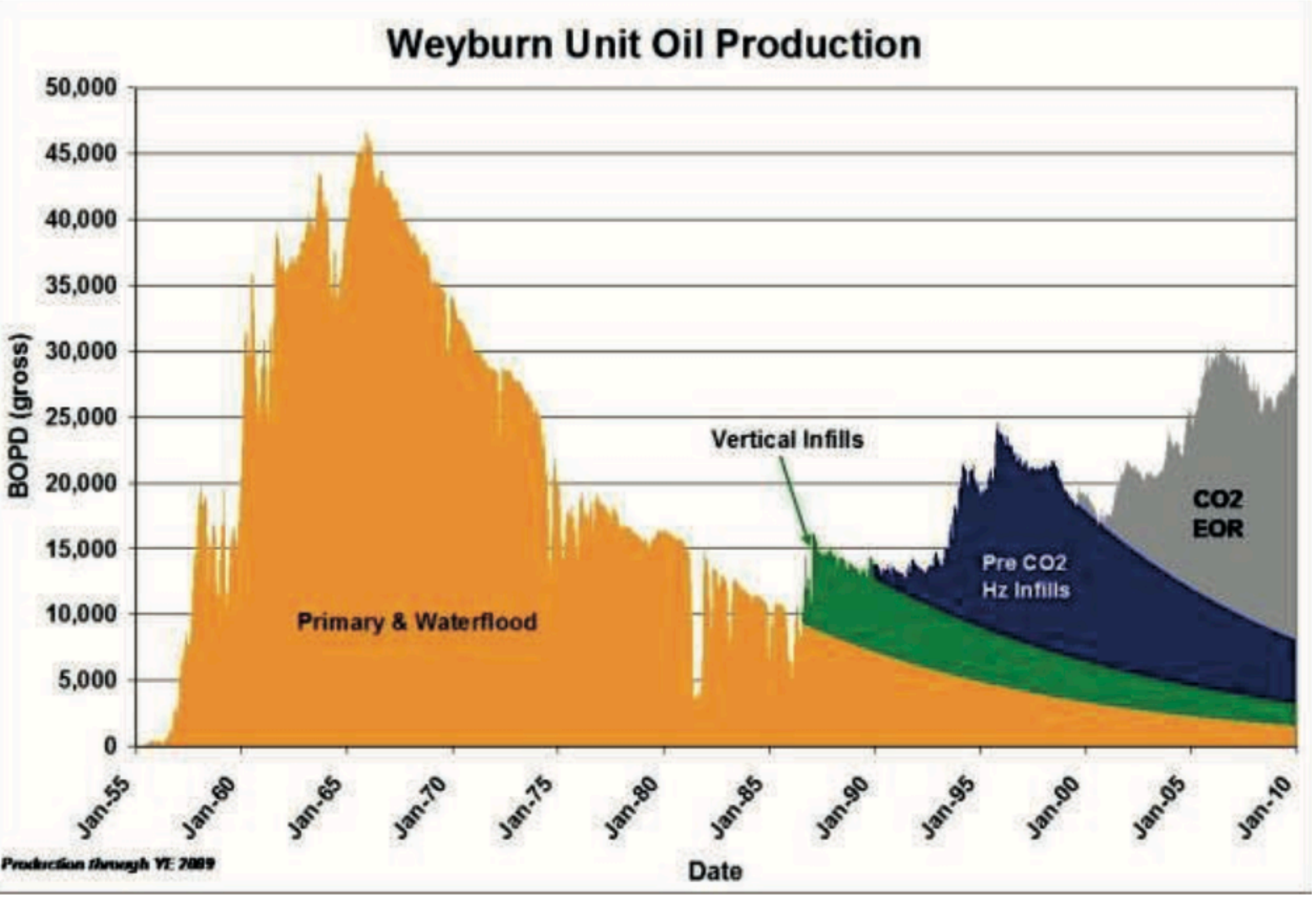
B Difficult-to-eliminate emissions, 2014 (9.2 Gt CO_2)

2014: 9.2 Gt/yr CO_2

From Davis et al., 2018, Science.

Carbon Capture, Utilization and Sequestration Here Today

Here Today: CO_2 Enhanced Oil Recovery & Sequestration

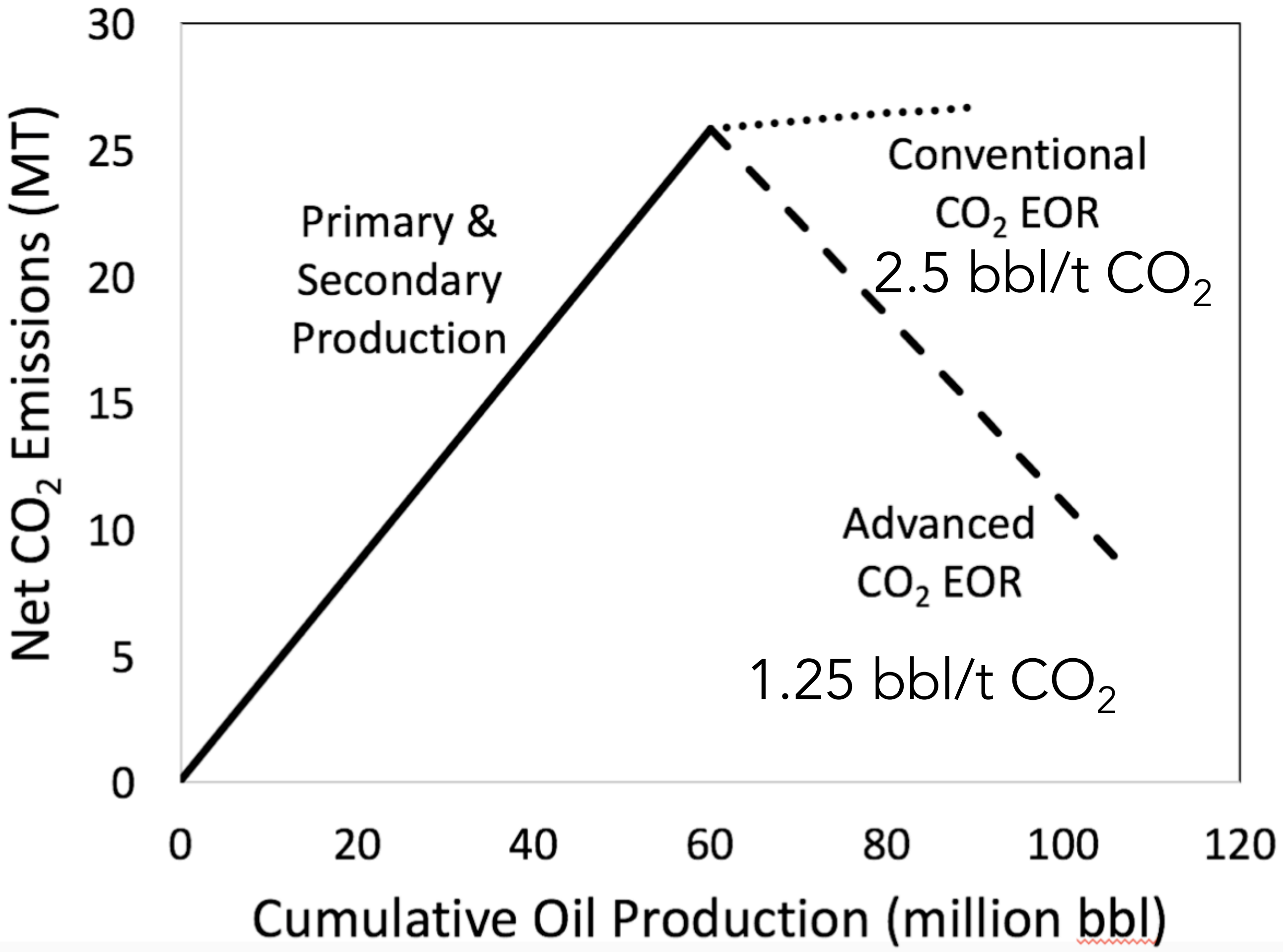


Conventional CO_2-EOR

- 3% of U.S. oil production today from CO_2-EOR (300,000 bbl/day)
- 65 Mt/yr of CO_2 injection of which, 21 Mt/yr from anthropogenic sources
- 60 to 360 Gt CO_2 sequestration technical potential

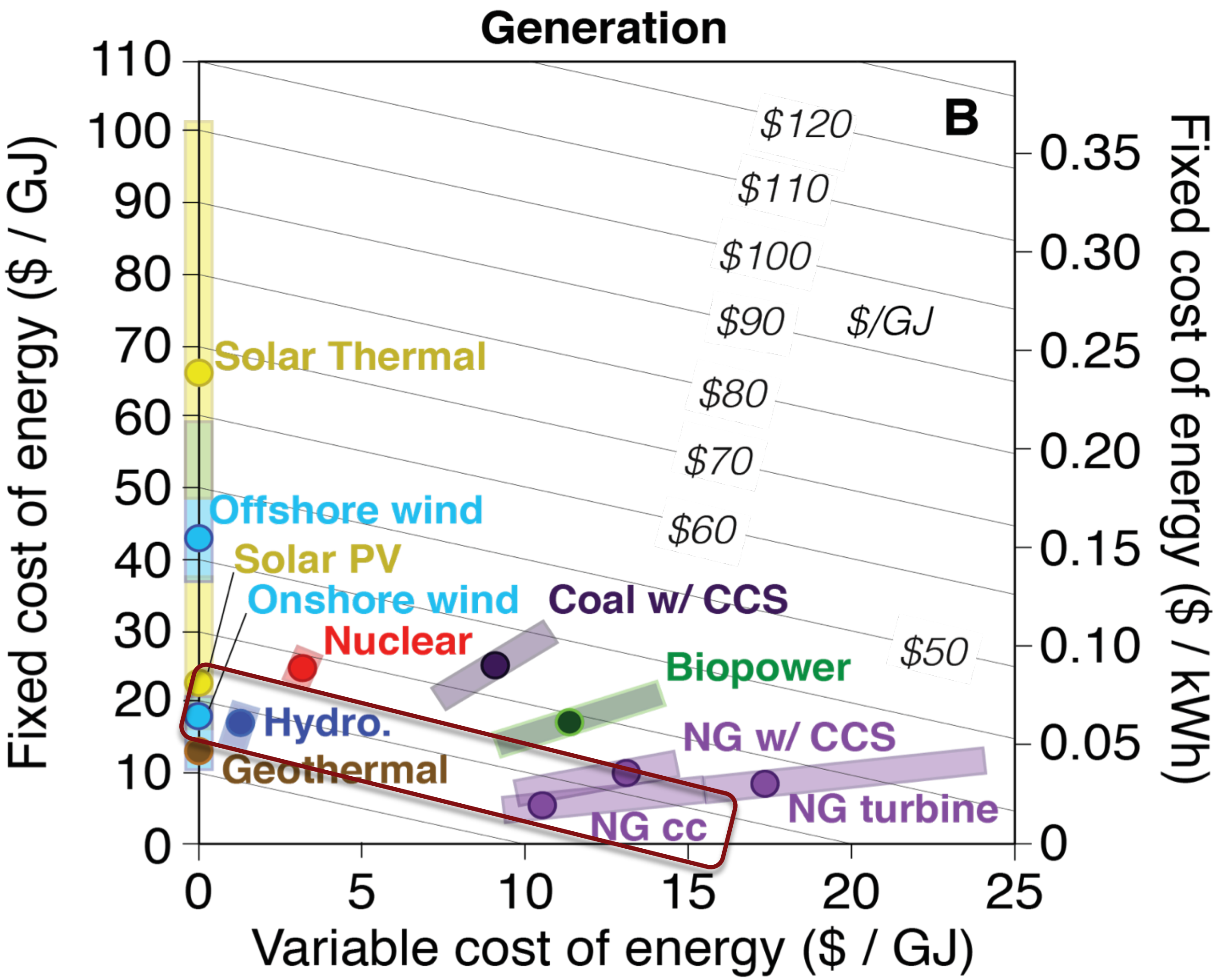
Producing Carbon Neutral or Carbon Negative Oil with Advanced CO_2-EOR

- Increase ratio of CO_2 injected per barrel of oil produced
- Conventional CO_2-EOR 2.5 bbl/t CO_2
- Doubling or tripling yields high ultimate recovery and provides Gt scale CO_2 reductions
- 75 million tonnes of high purity CO_2 are available to accelerate early deployment



Benson and Deutch, 2018, Joule.

Cost Must Come Down for Widespread Deployment of Carbon Capture and Sequestration From Power Plants



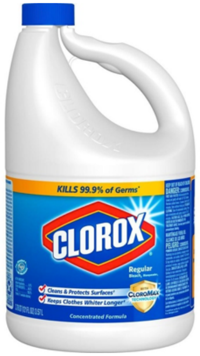
- Advanced combustion (e.g. Allam Cycle)
- New materials and processes for CO_2 capture (e.g., MOFs)

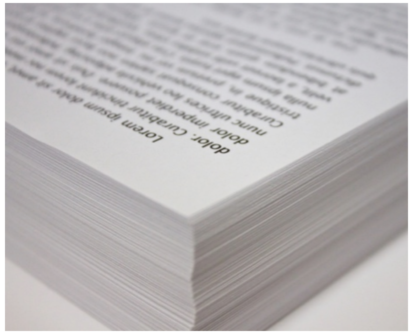
Petra Nova 240 MW coal-fired generation with post combustion capture: 1.4 Mt CO_2/ year .

Electrochemical Manufacturing

Electrochemical manufacturing has been essential to modern society

Electrochemical aluminum production – ***63 billion kg/yr*** – *9 kg/person/yr* – $130 billion market



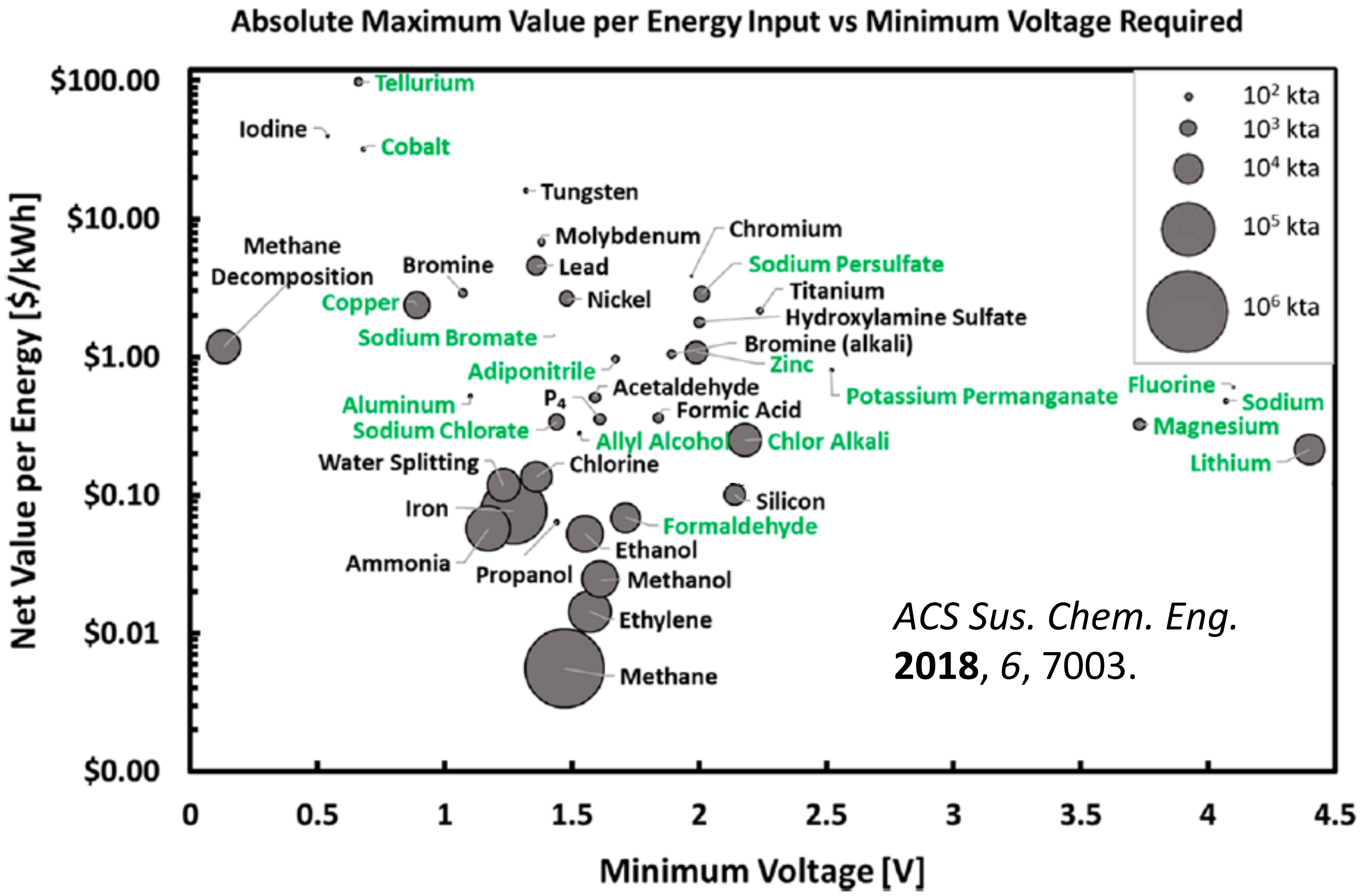


Chloro alkali electrolysis – ***65 billion kg/yr*** – *9 kg/person/yr* – 1000+ products

Large-scale electrochemical manufacturing processes are often limited by electricity costs

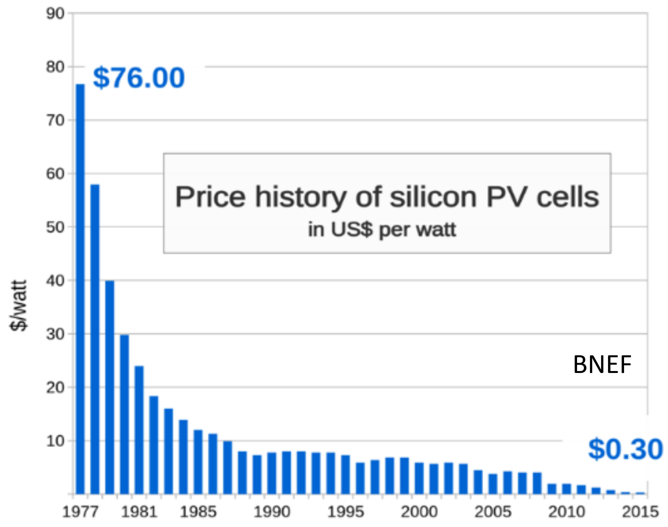
Many large volume commodities have low value relative to the energy input indeed for electrochemical production:

- Lower electricity costs are critical to economic viability of electrochemical manufacturing
- Capital cost reductions for electrolysis technologies are essential

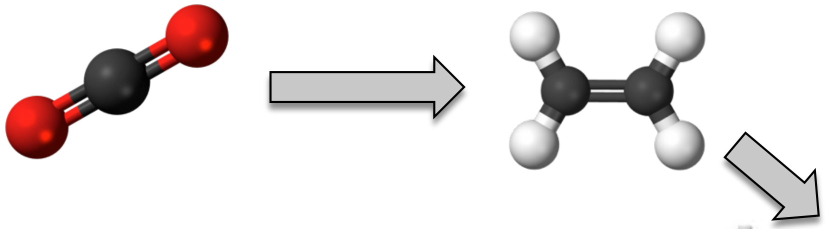


ACS Sus. Chem. Eng. **2018**, *6*, 7003.

Low-cost low-carbon energy enables a renaissance in electrochemical manufacturing

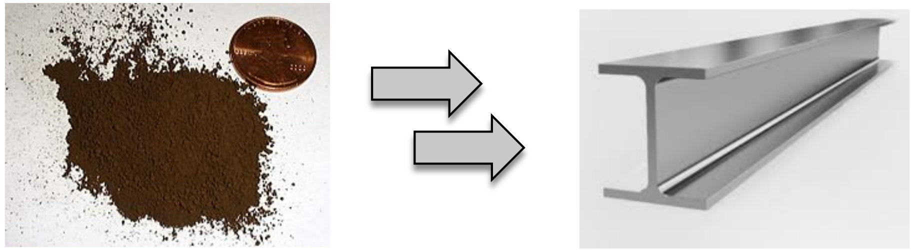


Enables electrochemical manufacturing of **plastics**:



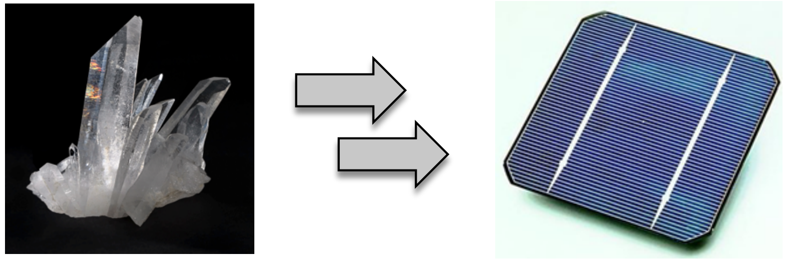
Can allow for net negative emissions $400 billion market

Enables electrochemical **steel production**:



Currently generates 5% of global CO_2 emissions; $750 billion market

Electrochemical **silicon production**:



Dramatically reduces carbon emissions payback time of solar; $6 billion market

Renewed investment in electrochemical science and engineering is key to US competitiveness

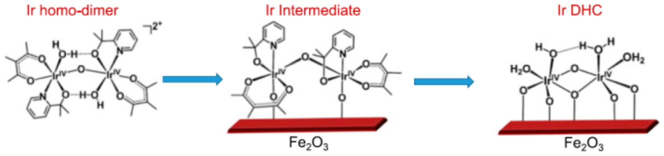
Innovations in electrochemical science needed to reduce energy demand and expand the number of viable processes

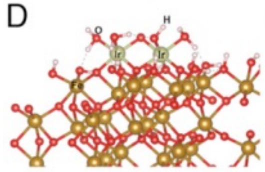
- Durable, inexpensive, efficient electrochemical catalysts
- Better understanding/control over selectivity in electrochemical processes
- Control of interfacial chemistry at the molecular/atomic level

Innovations in electrochemical engineering needed to lower capital costs of electrolysis technologies

- Inexpensive and robust membranes/separators
- Scalable and durable electrolytes
- Stable anode and cathode materials under extreme environments

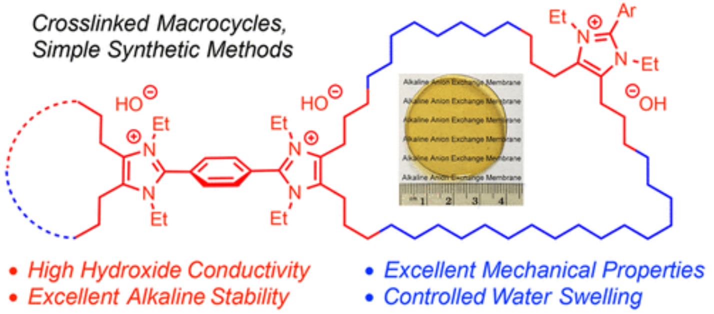
Atomically precise water oxidation catalysts





PNAS **2018**, *115*, 2902

Durable anion exchange membranes

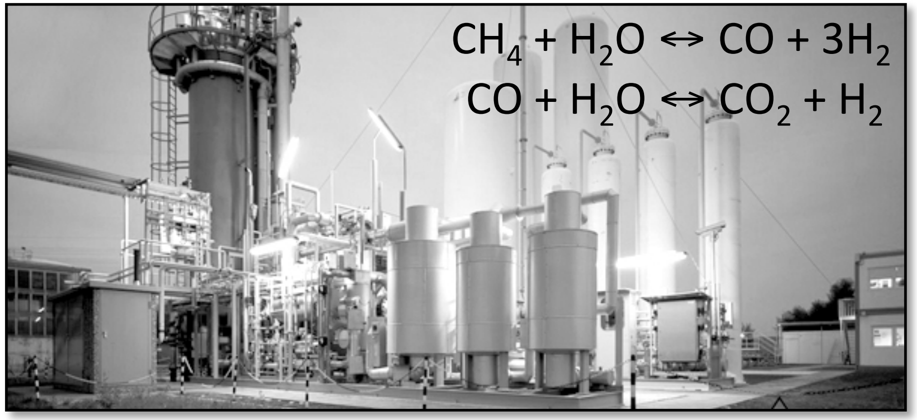


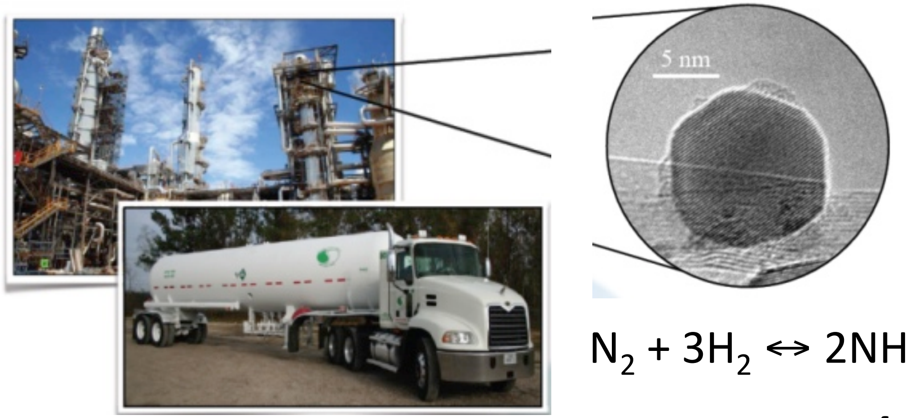
Macromolecules, **2018**, *51*, 3212

39

Fuels for Industry: Can we economically produce hydrogen from water?

Fundamental R&D underpins the success of today's fuels and chemicals industry





$N_2 + 3H_2 \leftrightarrow 2NH_3$

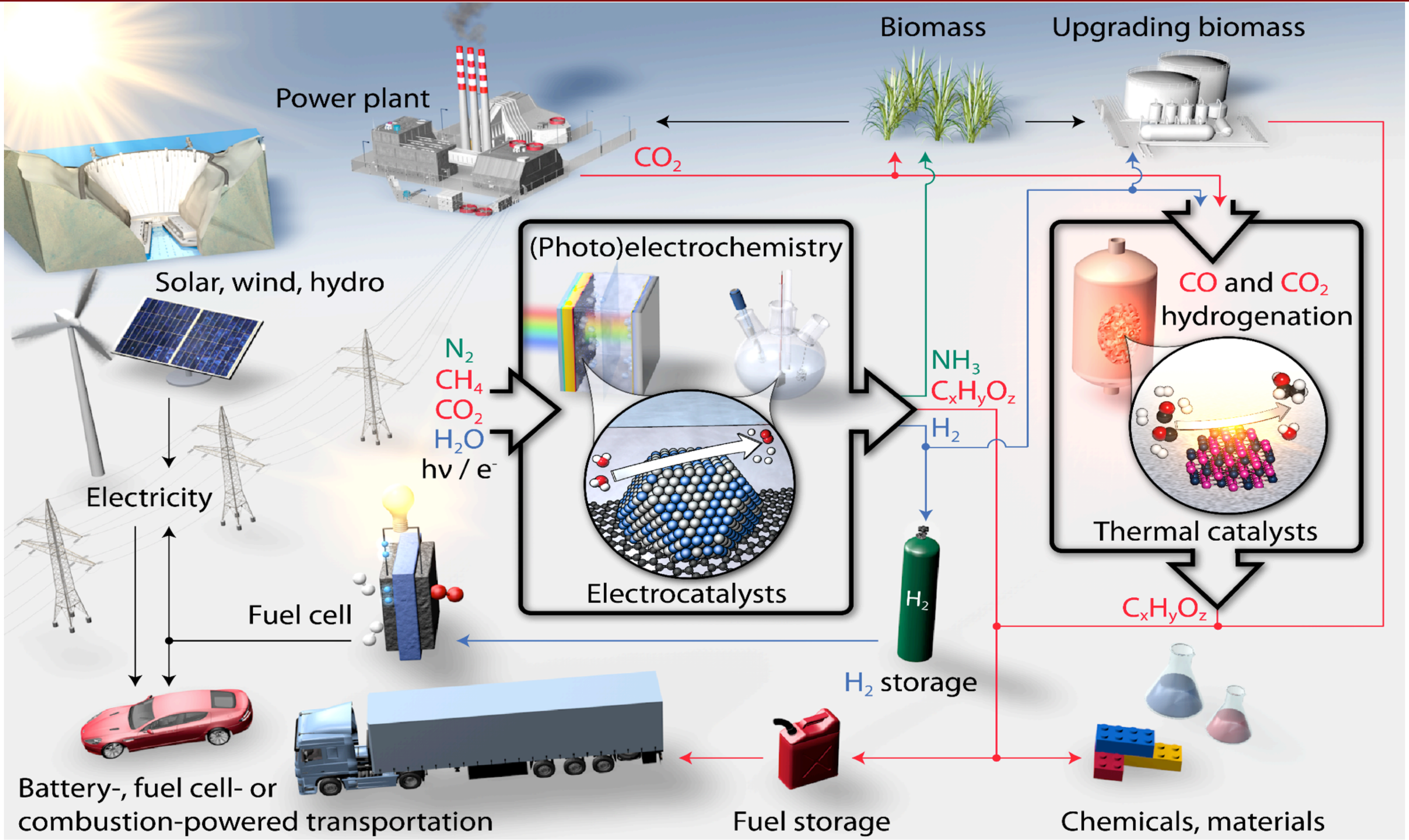
H_2 production by steam reforming — H_2 — ***65 billion kg/yr*** *9 kg/person/yr*

NH_3 production by Haber-Bosch — NH_3 — ***150 billion kg/yr*** *20 kg /person/yr*

Petroleum refining — **gasoline** — ***1 trillion kg/yr*** *130 kg/person/yr*

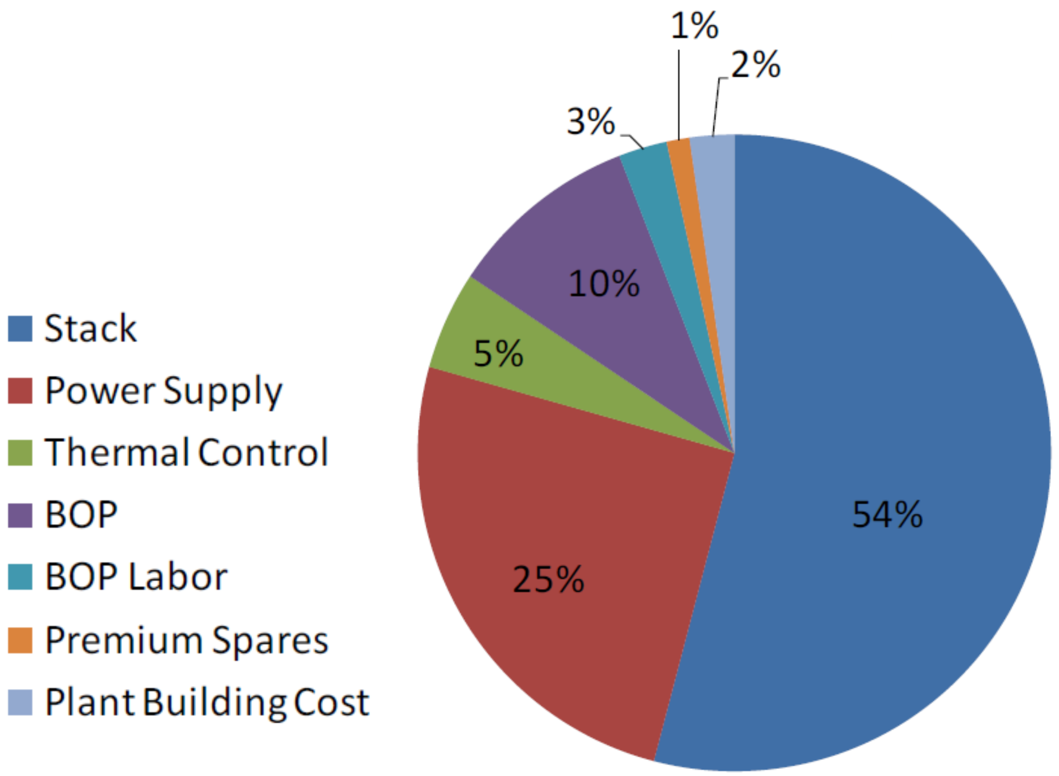
Plastics production — **plastics** — ***300 billion kg/yr*** *40 kg/person/yr*

Catalyzing a Sustainable Future

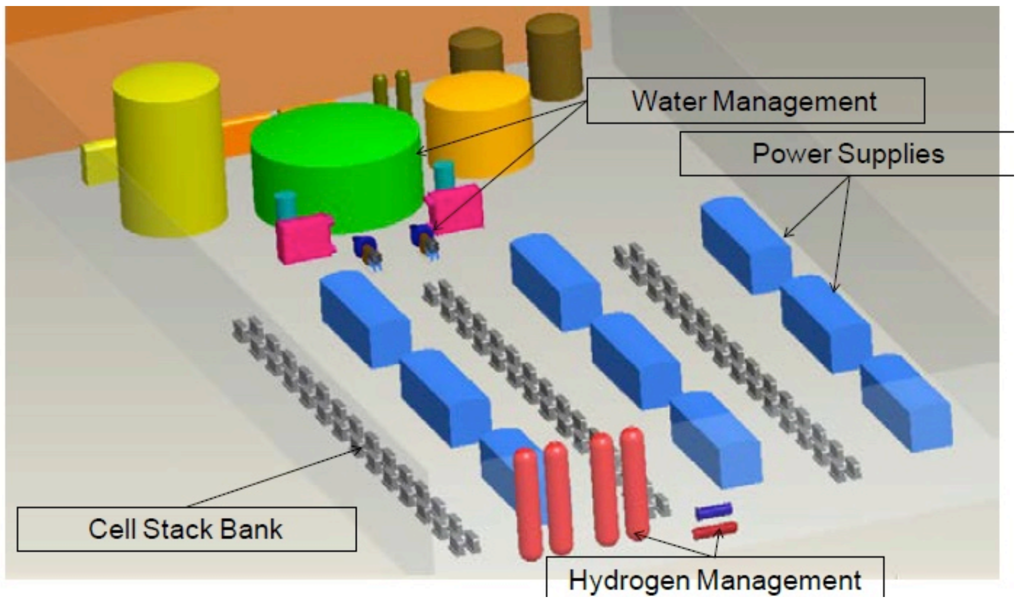


Z. Seh, J. Kibsgaard, C.F. Dickens, I. Chorkendorff, J.K. Nørskov, T. F. Jaramillo, *Science*, **355** 6321 (2017)

Large scale renewable H_2 production



Concept production plant
50,000 kg/day production
Total capital cost ~ **\$0.50-\$0.60/kg H_2**
(less land)



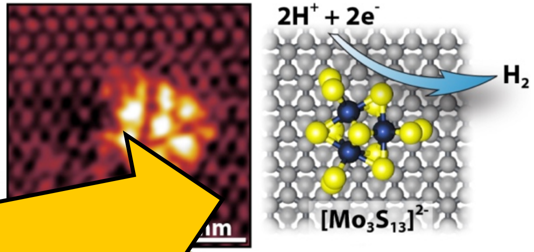
Kathy Ayers, Proton Onsite, DOE EERE Annual Merit Review (2013).

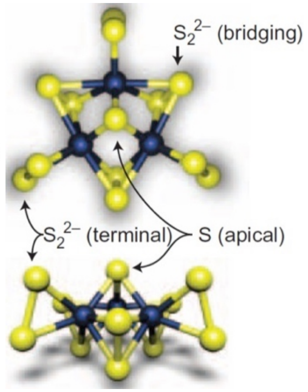
Developing non-precious metal H_2 catalysts

U.S. DOE Office of Science
Energy Frontier Research Center (EFRC)

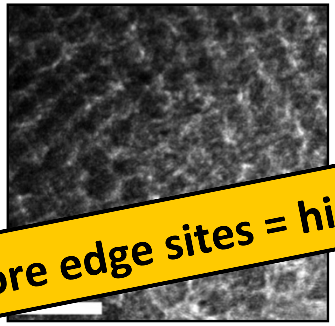
U.S. DOE Basic Energy Sciences (BES)
Catalysis Science

3. $[Mo_3S_{13}]^{2-}$ clusters
J. Kibsgaard, T.F. Jaramillo et. al., Nature Chemistry, **2014**, 6, 248.

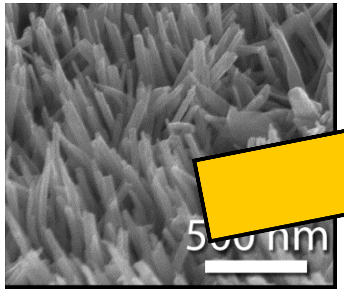


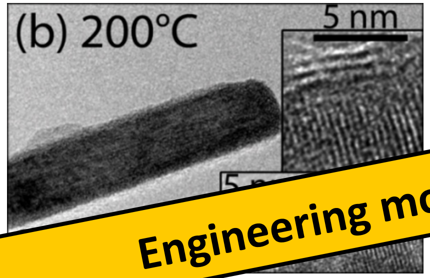


2. Mesoporous MoS_2
J. Kibsgaard, T.F. Jaramillo et. al., Nature Materials, **2012**, 11, 963.

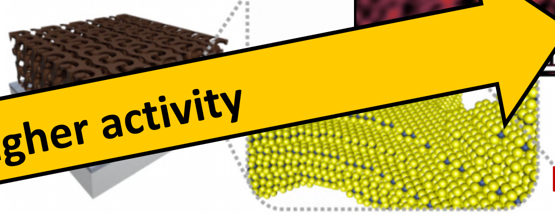


1. Core-shell MoO_3-MoS_2 nanowires
Z. Chen, T.F. Jaramillo et. al., *Nano Letters*, **2011**, 11, 4168.

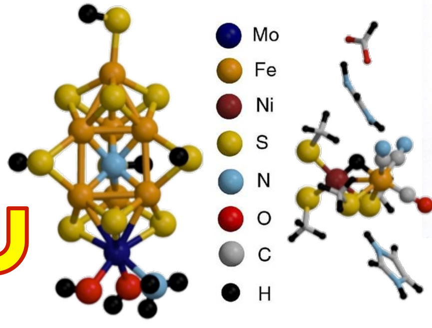


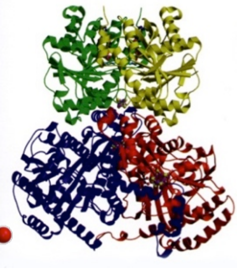


Engineering more edge sites = higher activity



Hydrogenase and nitrogenase

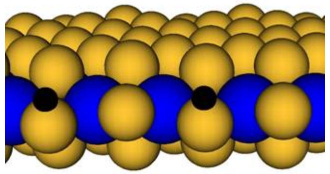




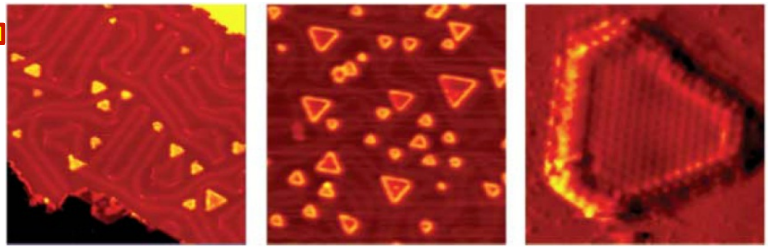
nitrogenase active site
ΔG_H= -0.07 eV

hydrogenase active site
ΔG_H= -0.06 eV

B. Hinnemann and J.K Nørskov, *J. Am. Chem. Soc.* **2004**, 126, 3920.



MoS_2 nanoparticles

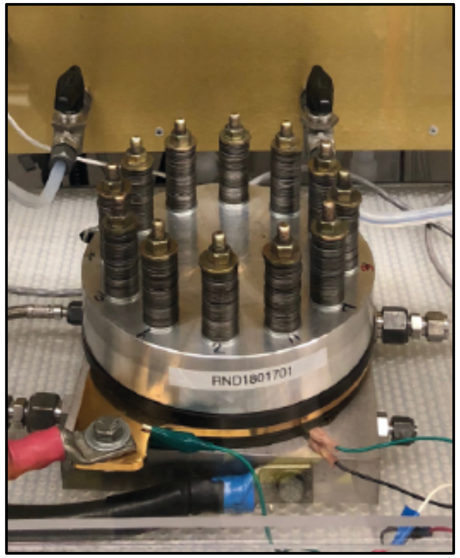


T.F. Jaramillo et. al., *Science*, **2007**, 317, 100.

Replacing platinum with non-precious metal H_2 catalysts in a commercial-scale water electrolyzer

The non-precious metal catalysts are efficient and durable under true operating conditions.

[Please see: L. King, M. Hubert, C. Capuano, J. Manco, N. Danilovic, E. Valle, T. R. Hellstern, K. Ayers, T. F. Jaramillo (2018), forthcoming.]

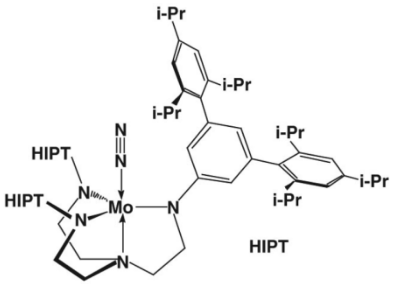


YOUR SOURCE FOR ALL THINGS HYDROGEN

Game Changing Opportunities: Foundational R&D on new catalysts, new processes creates a new industry for fuels and chemicals.

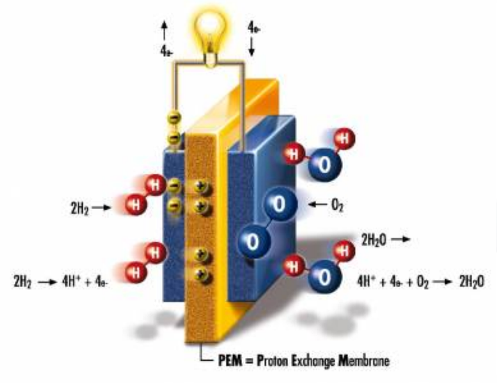
Biocatalysts
e.g. enzymes

H_2O oxidation in photosynthesis



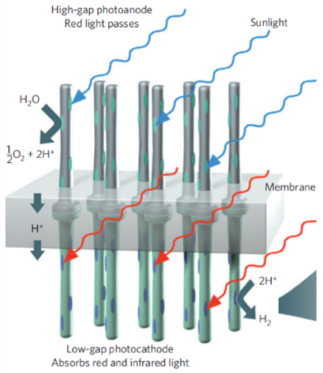
Homogeneous Catalysts
e.g. molecular complexes

Fine chemicals
Olefin metathesis



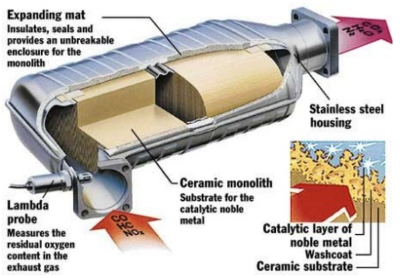
Electrocatalysts
e.g. Pt nanoparticles

Fuel Cells
Water electrolysis



Photocatalysts
e.g. GaAs/GaInP_2/Pt

Solar water-splitting
Water remediation



Thermal Heterogeneous Catalysts
e.g. Rh nanoparticles

Catalytic converters Oil refining

- **21st century inputs: new feedstocks (e.g. H_2O, CO_2), renewable electricity.**
- **Controlling chemical reactions at the level of atoms and molecules.**
- **New process designs, integrated systems.**
- **Developing physics-based models and leveraging data science for chemical discovery**
- **Harnessing biology for renewable fuel/chemical production**
- **Reimagining plastics**

High-Efficiency Manufacturing through 3-D Printing

Additive Manufacturing, Driving Innovation in Manufacturing

Revitalizing the US's Tool and Die Sector

1998 / **1/3rd**

Since **1998**, over **1/3rd** of US tool, die and mold establishments have gone out of business

50% / **52**

Also since '98, US mfg. employment has dropped **50%** and the avg. age of skilled workers is **52**

$1M / **9**

Typical tool sets cost **$1M** and have long lead times **(9 months)**

Compete / **Lean**

To be **competitive**, US tool & die manufacturers must become **lean**

*AM can enable lean tool and die manufacturing by **eliminating waste** and **increasing processing speeds***

What is Additive Manufacturing?

- Additive manufacturing (AM), or 3D printing, is the process of fabricating components from the bottom-up, layer-by-layer.
- Benefits of AM include but are not limited to:
  - Reducing **time, energy, material** associated with manufacturing tools, dies, molds and components.
  - Producing items **bigger, faster, cheaper, smarter** and with **complex** geometries.

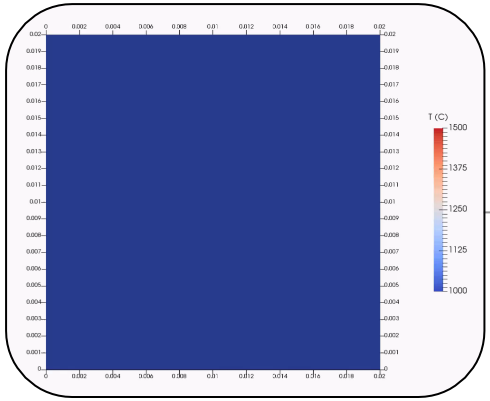
Using large-scale polymer deposition to 3D print 17.5' long Boeing tool

Oak Ridge National Laboratory

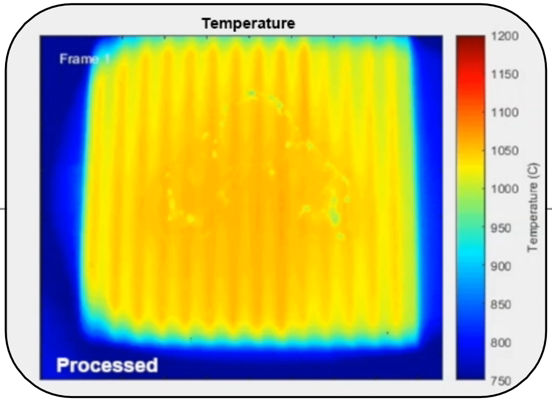
Model. Make. Measure.

"Fundamental science enabling manufacturing"

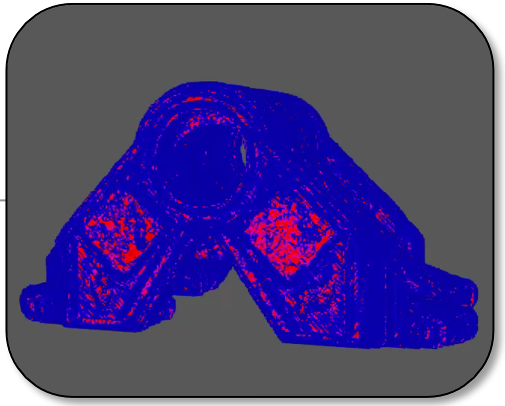
Model

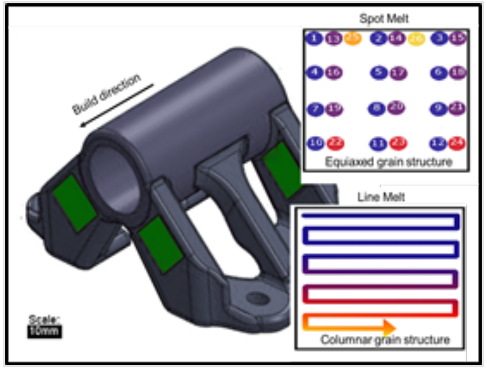


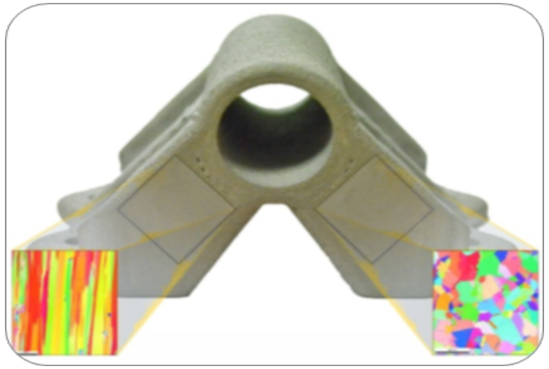
Make

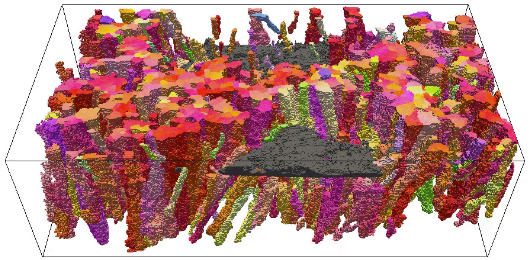


Measure



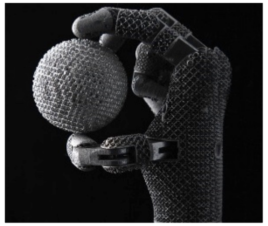






Wide Range of Additive Processes Lead to Game-Changing Technology

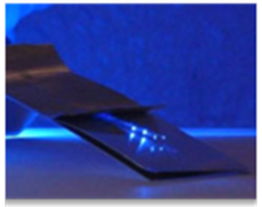
Electron Beam Melting



- Developing in-situ characterization, feedback, and control
- Heated powder bed
- Expanding range of materials (Ti64, CoCr, 625, 718)
- Precision melting of powder materials

CAD TO METAL® arcam Arcam AB®

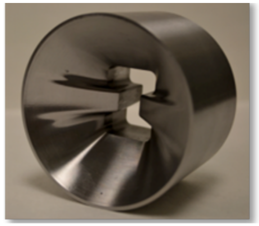
Ultrasonic Additive Manufacturing



- Simultaneous additive and subtractive process for manufacturing complex geometries
- Solid-state process allows embedding of optical fibers and sensors

SOLIDICA

Laser Metal Deposition



- Site-specific material addition
- Application of advanced coating materials for corrosion and wear-resistance
- Repair of dies, turbines, etc.

POM

DM3D

Selective Laser Melting

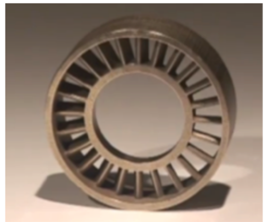
- Unheated powder bed
- Wide range of material choices (316L, 17-4PH, H13, Al, Ti, 718, 625)
- Precision melting of metal powders
- Up to 630 x 400 x 500mm build volume

RENISHAW

CONCEPTLASER

SLM Solutions GmbH

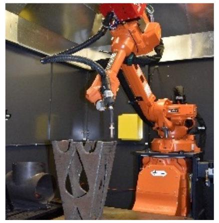
Metal Binder Jetting



- Metal matrix composites and sintered materials including:
- Stainless steel + bronze
- Tungsten + titanium
- Ceramics + sand
- Large build volumes (10 x 10 x 16in)
- Fast build times (30 sec/layer)

ExOne™ DIGITAL PART MATERIALIZATION

Large-Scale Welding

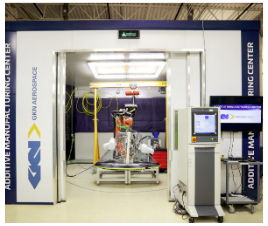


- Open-air environment
- MIG welding arm with 6 DOF and 2 rotational degrees
- Print size not restricted
- Uses low-cost welding torches and wire
- CAD-to-path functionality

WOLF ROBOTICS

LINCOLN® ELECTRIC

Large-Scale Laser Metal



- Reducing buy-to-fly ratio of aerospace components
- Using 4kW laser and two 10kW lasers to melt Ti64 wire
- Inert system with argon-filled tent
- Prints ~10cubic inches/hr.

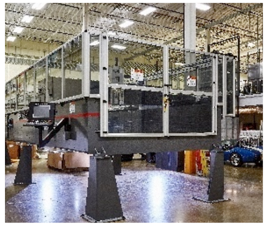
GKN

Hot Isostatic Press

- First rapid-quench HIP in America
- 180mm diameter
- Can reach pressures of 25,000psi
- Cooling rates of 3000C/min when cooled from 3000C
- Can HIP and heat treatment in same cycle

Quintus

Large-Scale Polymer Deposition



- Deposits up to 1000lbs. of pellet feedstock material per hour
- Build volume up to 20' long x 6' wide x 8' tall
- Printed >37 different polymers and composites
- Dual material capabilities

CINCINNATI®

Ingersoll Large-Scale Polymer Deposition

- Under development
- Will have 46' x 23' x 10' build volume
- Target deposition rate of 1000 lbs./hr.
- Will be 10x larger and faster than previous commercial systems

INGERSOLL Machine Tools

Thermoset Dual Material Extrusion

- Capable of depositing 300mL/minute
- Can control material properties and speed on the fly
- Cross-linking between layers
- 2-part resin

ShopBot®

PPG

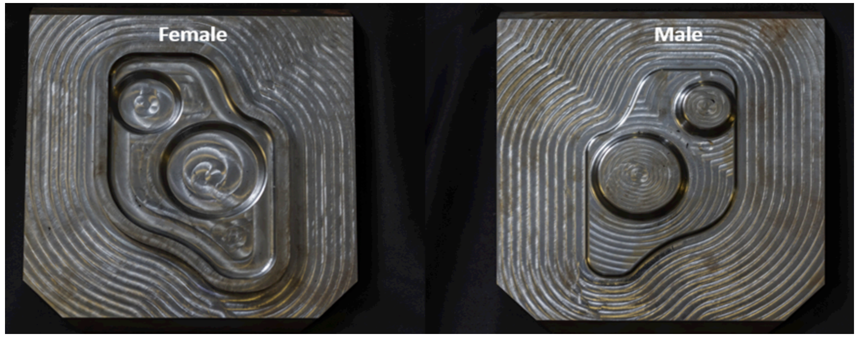
Fortus MC

- ~0.005" – 0.007" resolution
- Up to 914 x 610 x 914mm build volume
- 0.5 – 1.5 in3/hr.
- Ultem and ABS

Stratasys FOR A 3D WORLD™

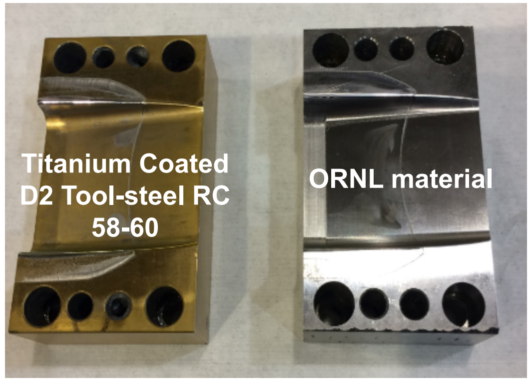
Industry 4.0: Producing a Die in a Day

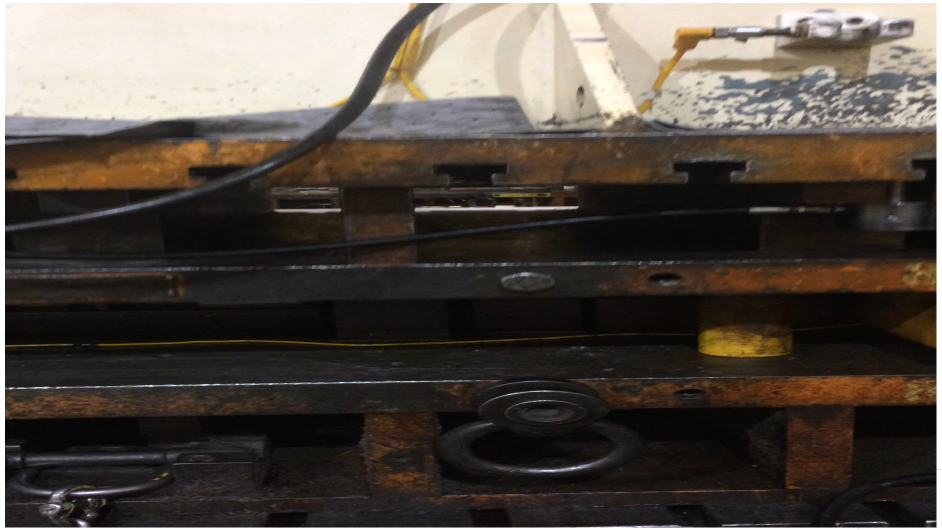
Showcasing additive capabilities to over 130,000 people



ORNL and industry illustrated the concept of producing a "Die in a Day" at the International Manufacturing Technology Show, the largest manufacturing conference in N. America. Over **130,000** attendees had the chance to witness 5 dies being **designed, printed, machined** and **utilized** to mold parts on the show floor.

ORNL also displayed examples of previously-printed dies for industry, including a Whirlpool die which has been used to fabricate **>76,000** parts.





Thank you

Khaili Amine (Argonne National Lab)
Robert Armstrong (MIT)
Michael Aziz (Harvard)
Angela Belcher (MIT)
Sally Benson (Stanford)
Craig Blue (ORNL)
Fikile Brushett (MIT)
Vladimir Bulović (MIT)
Jeremy Carl (Hoover/Stanford)
Yet-Ming Chiang (MIT)
Christopher Chidsey (Stanford)
Steve Chu (Stanford)
Will Chueh (Stanford/SLAC)
Yi Cui (Stanford/SLAC)
Emily Dahl (MIT)
David Fedor (Hoover/Stanford)
Sharon Hammes-Schiffer (Yale)
Thomas Jaramillo (Stanford/SLAC)
Matt Kanan (Stanford)
Jay Keasling (UC-Berkeley/LBL)
Jun Liu (PNNL)
Arun Majumdar (Stanford/SLAC)
Michael McGehee (U. Colorado, Boulder/NREL)
Carl Mesters (Shell)
Ernest Moniz (MIT)
Francis O'Sullivan (MIT)
Kristala Prather (MIT)
Yuriy Román-Leshkov (MIT)
Yang Shao-Horn (MIT)
George Shultz (Hoover/Stanford)
Alfred Spormann (Stanford)
Thomas Stephenson (Hoover/Stanford)
Yogesh Surendranath (MIT)
Jud Virden (PNNL)
Dennis Whyte (MIT)
Virginia Wright (INL)