Carbon Hub

ICR23 Innovations in Climate Resilience
Columbus, OH, 28-30 March 2023

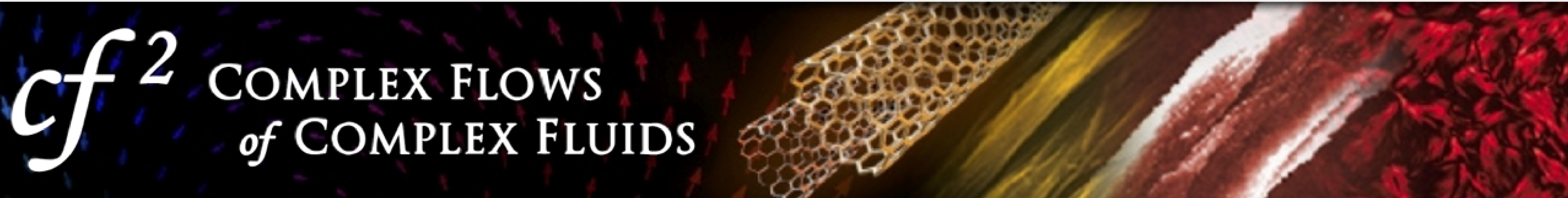
RICE

We can use carbon to decarbonize—and get hydrogen for free

6 12.011
C
Carbon

1 1.000
H
Hydrogen

Matteo Pasquali
Departments of Chemical & Biomolecular Engineering,
Chemistry, Materials Science & NanoEngineering
The Carbon Hub; The Smalley-Curl Institute
Rice University, Houston, TX; mp@rice.edu



THE PROBLEM WE ARE FACING

We must decarbonize

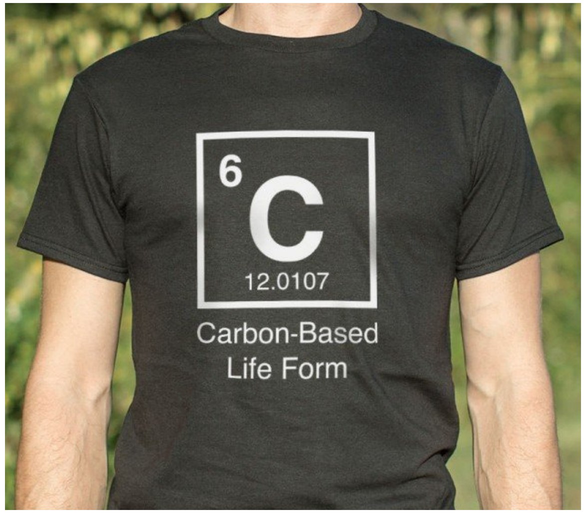
Source: NASA

THE PROBLEM WE ARE FACING

We are carbon-based life forms

In dry mass

- 50+% of our body is carbon
- 50+% of our food is carbon
- 50+% of our clothes are carbon



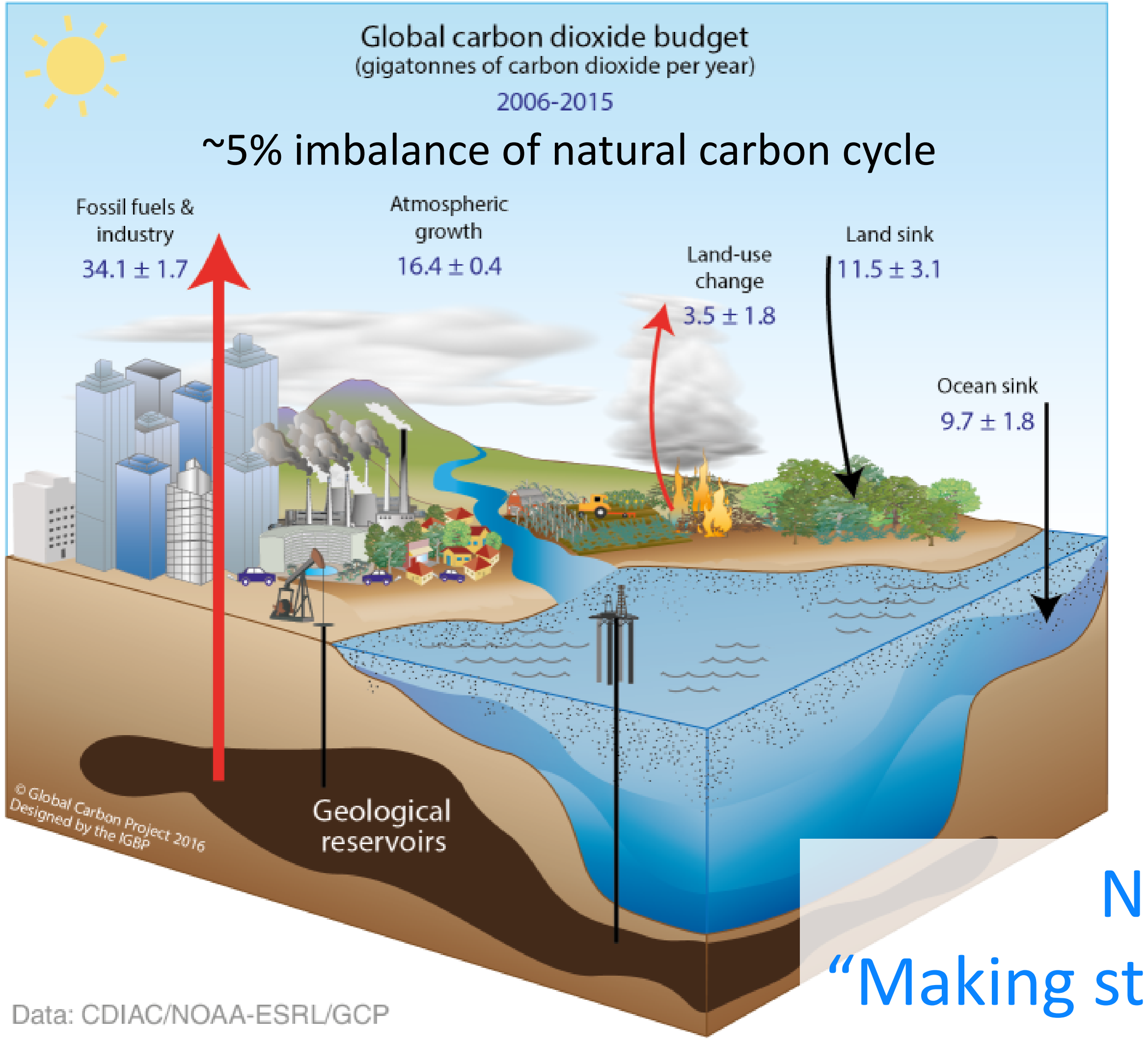
Source: NASA

We must decox

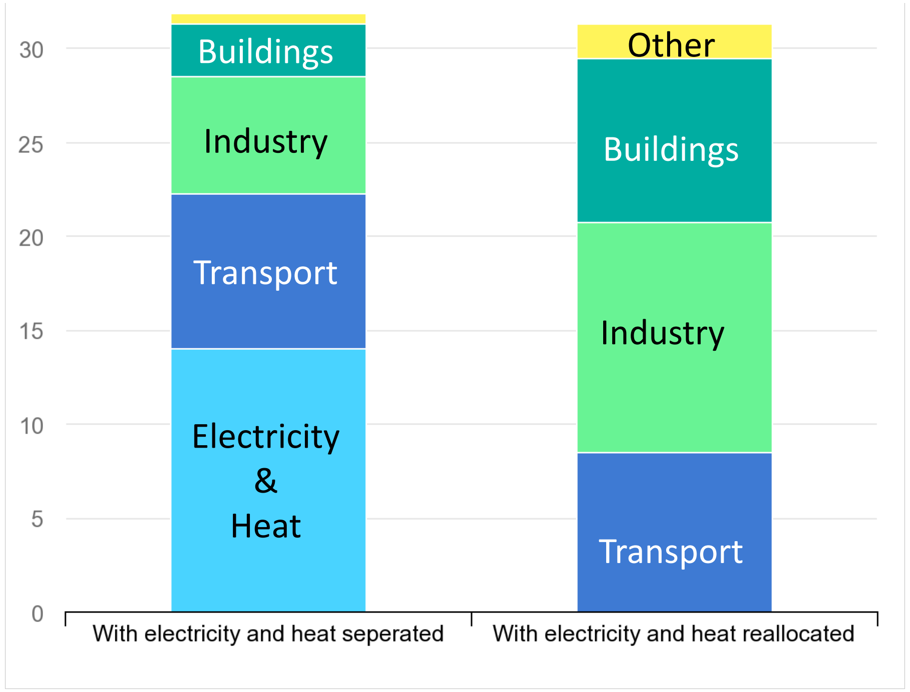
The problem is Carbon Dioxide

We have a language challenge: we use the same word for C and CO_2

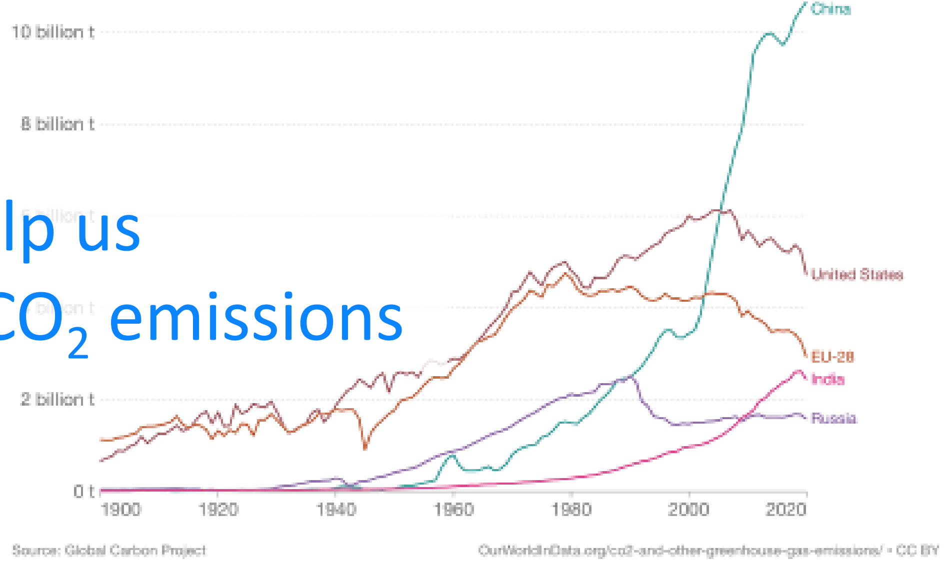
MAN-MADE PERTURBATION OF GLOBAL CARBON CYCLE



Data: CDIAC/NOAA-ESRL/GCP



(excluding land-use change)



Source: Global Carbon Project

OurWorldInData.org/co2-and-other-greenhouse-gas-emissions/ • CC BY

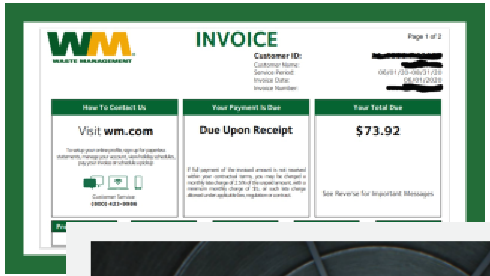
Nature can help us

“Making stuff” causes CO_2 emissions

ONE APPROACH: CCS

- Carbon (Dioxide) Capture and Storage
- Sometimes called Carbon Management
- Allows continued use of fossil fuels
- CO_2 as waste management problem
  - Pay to remove
  - Pay to store (landfill)

- Total urban waste: 2 GT/yr
- Total CO_2 emissions: 37 GT/yr
- At 100 $/Ton for CCS
  - 3.7 Trillion $/yr business
  - ~60% of the global O&G industry
  - ~5% of world GDP



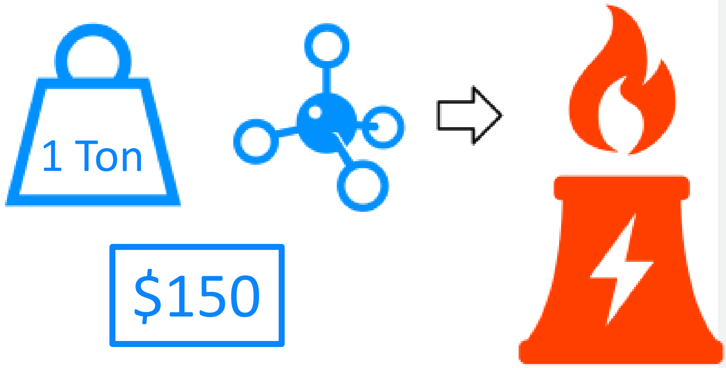
INVOICE

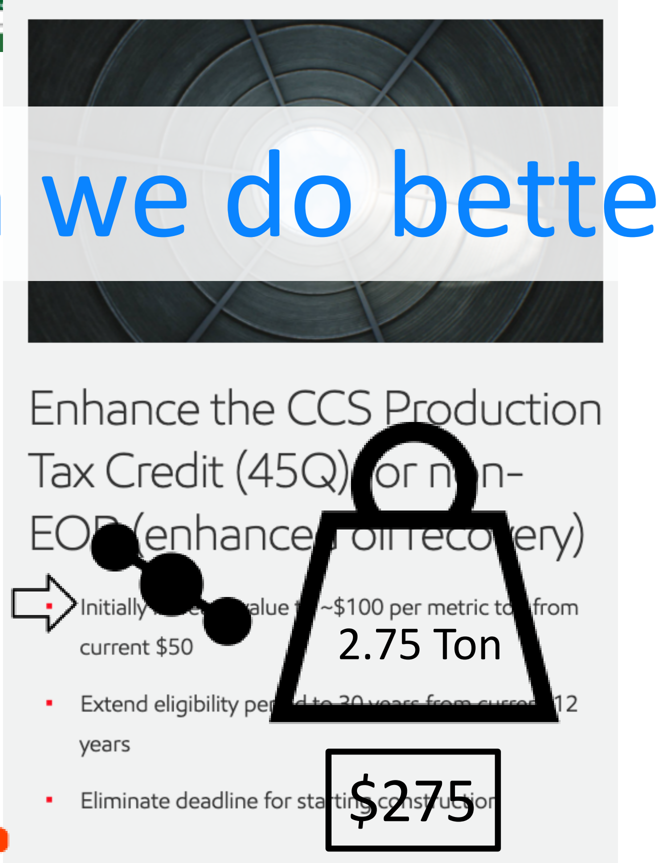
Page 1 of 2

Customer ID: [redacted]
Customer Name: [redacted]
Service Period: 06/01/20-06/31/20
Invoice Date: 06/01/2020
Invoice Number: [redacted]

How To Contact Us	Your Payment Is Due	Your Total Due
Visit wm.com Customer Service	Due Upon Receipt	$73.92 See Reverse for Important Messages

Can we do better?





Enhance the CCS Production Tax Credit (45Q) for non-EOR (enhanced oil recovery)

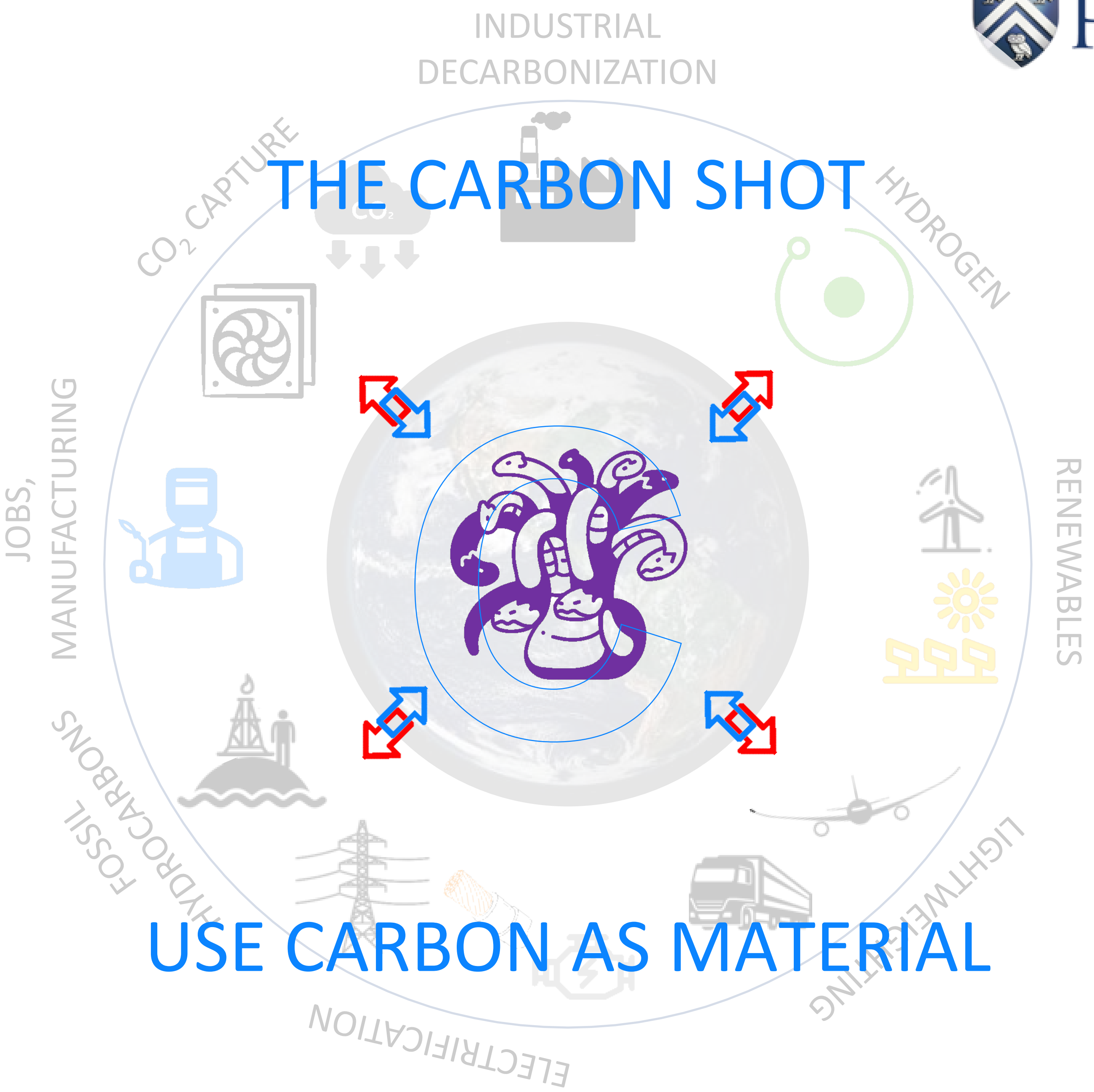
- Initially [illegible] value to ~$100 per metric ton from current $50
- Extend eligibility period to 30 years from current 12 years
- Eliminate deadline for starting construction

CLIMATE SOLUTIONS

- Multiple climate solutions
  - We need "all of the above"

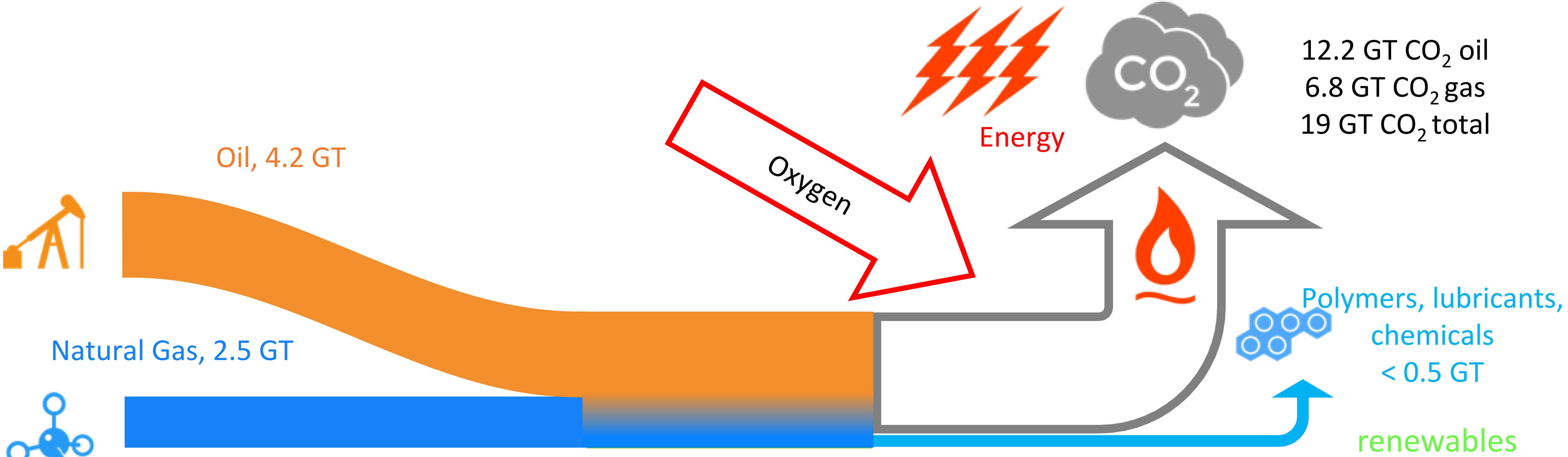
- Conflicting drivers
  - Each proposed path makes others harder

We're fighting a Hydra!



HOW DO WE CURRENTLY USE FOSSIL HYDROCARBONS?

(2017 data)

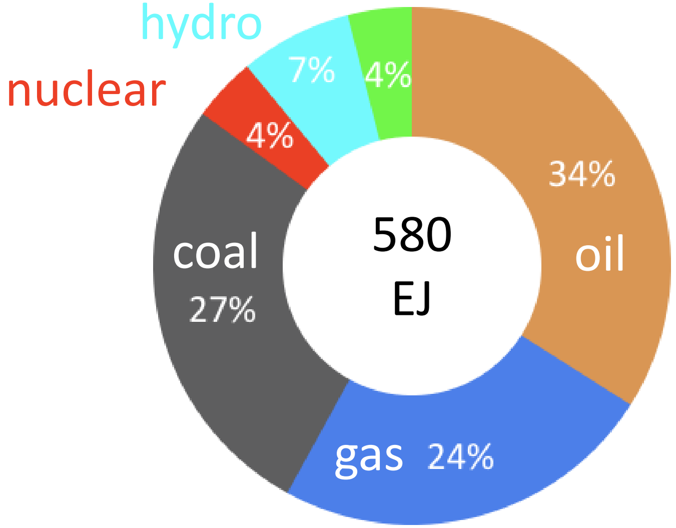


12.2 GT CO_2 oil
6.8 GT CO_2 gas
19 GT CO_2 total

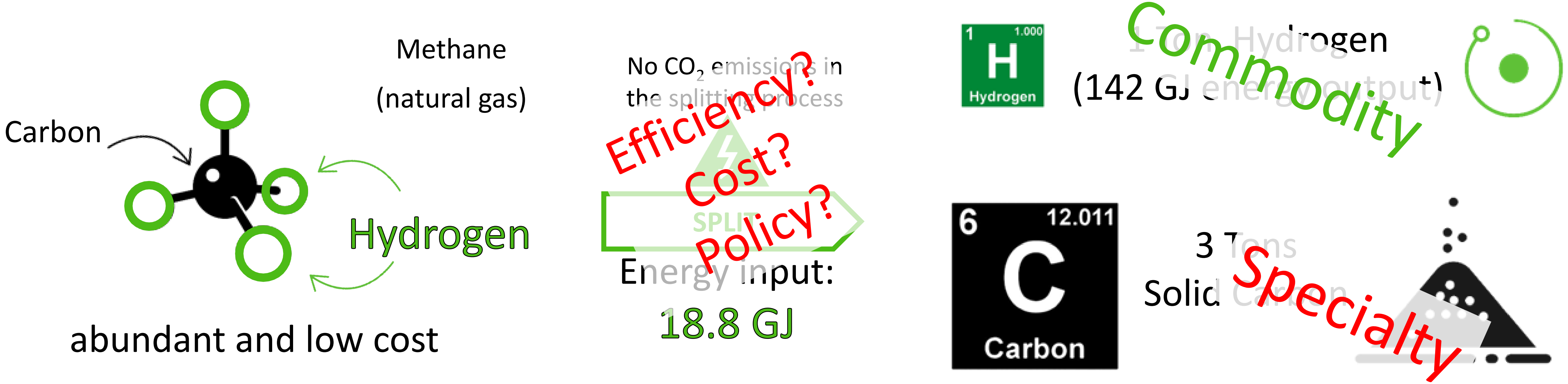
Polymers, lubricants,
chemicals
< 0.5 GT

- ⬡ Concurrent pressures:
  - ⬡ Displace fossil fuels with renewables
  - ⬡ Increase energy supply

Can we use the carbon as material?
Can we use the hydrogen as energy?



SPLITTING HYDROCARBONS



Carbon

Methane

(natural gas)

Hydrogen

abundant and low cost

No CO_2 emissions in the splitting process

SPLIT

Energy input:

18.8 GJ

Efficiency?

Cost?

Policy?

1 Ton Hydrogen

(142 GJ energy output)

Commodity

3 Tons

Solid Carbon

Specialty

Current Markets for Carbon Materials

Carbon black	Graphite	Carbon Fibers	Other
15 MT / yr	1 MT / yr	100 kT / yr	50-100 kT / yr

Structural Integrity

Cost

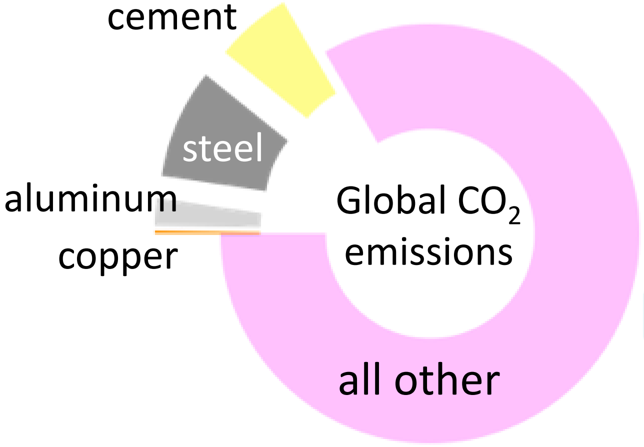
Energy Cost

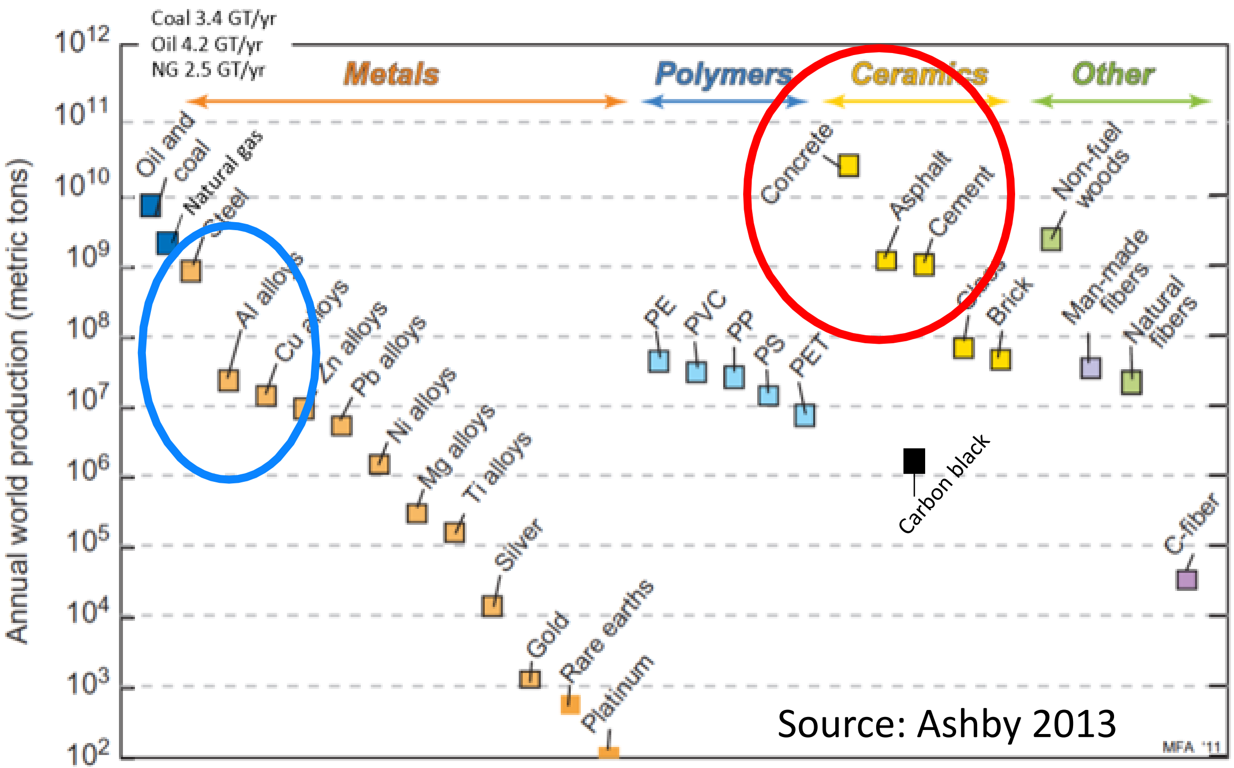
CO_2 footprint

MAKING STUFF: HOW MUCH MATERIALS DO WE USE?

High value: \$0.8 - 7 / kg
Used in transportation

Big offenders for
industrial CO_2 emissions?
Cement, steel, primary
metals





Source: Ashby 2013

FIGURE 2.3 *The annual world production of 27 materials on which industrialized society depends. The scale is logarithmic. The log scale conceals the great differences; the production of steel, for instance, is one billion (10^9) times larger than that of platinum.*

Low value: \$0.05 / kg
Used only in static
structures


Bauxite mining and deforestation in Brazil

Structural integrity is key for widespread use

The "right" carbon could displace emissions from industrial materials

ENVIRONMENTAL IMPACT

- Escondida Copper mine (Chile)
  - 1.1 MT/yr production
  - Tailing pond: ~ 20 km2
  - Main pit: ~6 km2
  - Whole site: > 200 km2

Imagery ©2017 Landsat / Copernicus, Map data ©2017 Google United State

- Perdido oil platform (Gulf of Mexico)
  - Oil: 100 kb/day (5MT/yr)
  - Gas: 200 M cft/day (1.8 MT/yr)
  - 5.5 MT/yr carbon
  - 1 MT/yr hydrogen

ENVIRONMENTAL IMPACT

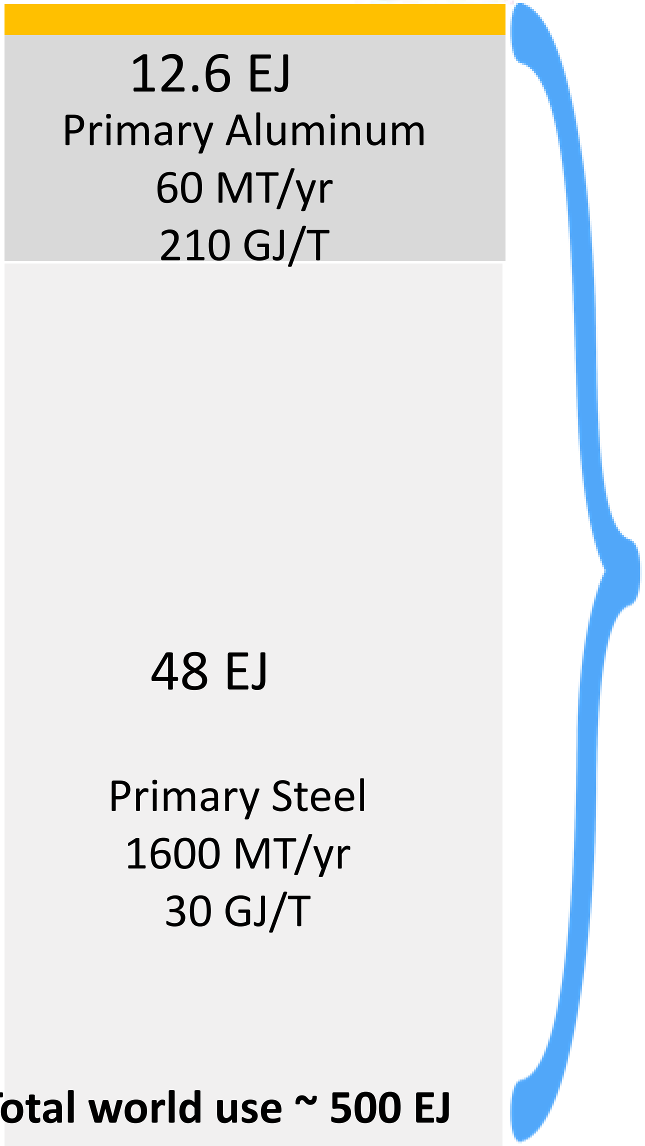
Copper is currently mined at 0.3% ore concentration

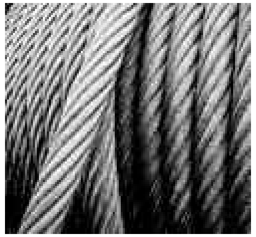
1 Ton of ore yields 3 kg of copper

Perdido to scale (~100 m)

INDUSTRIAL SECTOR: MATERIALS-ENERGY-CO_2 NEXUS?

Primary Copper
20 MT/yr
60 GJ/T





1 EJ ~ 1 Quad; Total world use ~ 500 EJ

Here's a question you should ask about every climate change plan

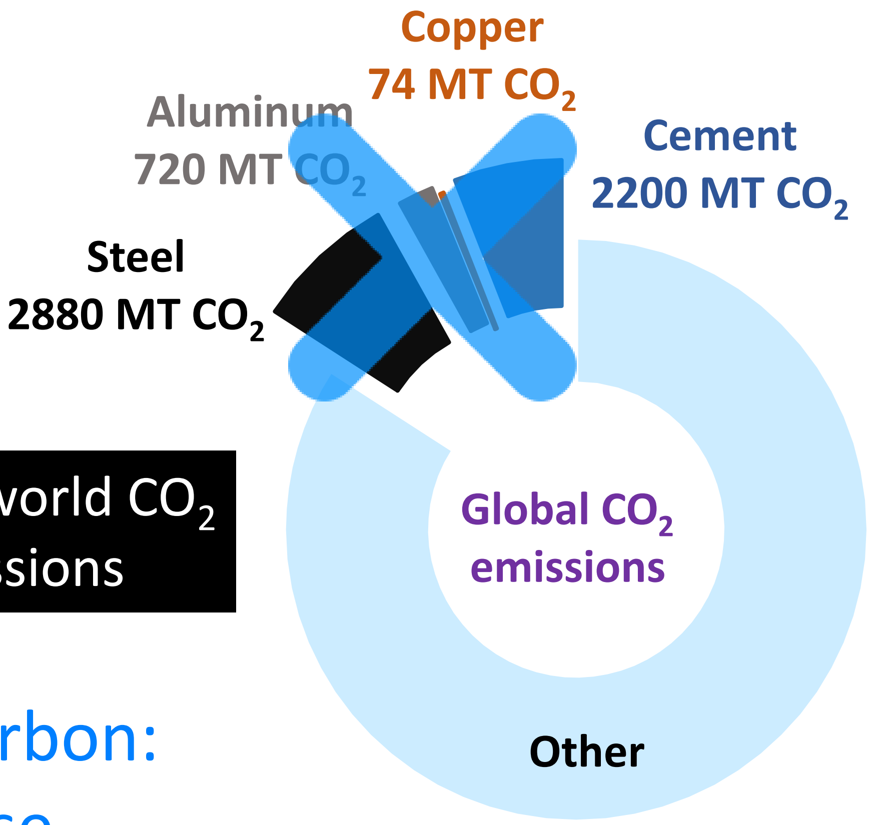
–I always ask this question: "What's your plan for steel?"

Bill Gates, August 2019

The plan for steel:
replace it!

12% of world energy use

16% of world CO_2 emissions

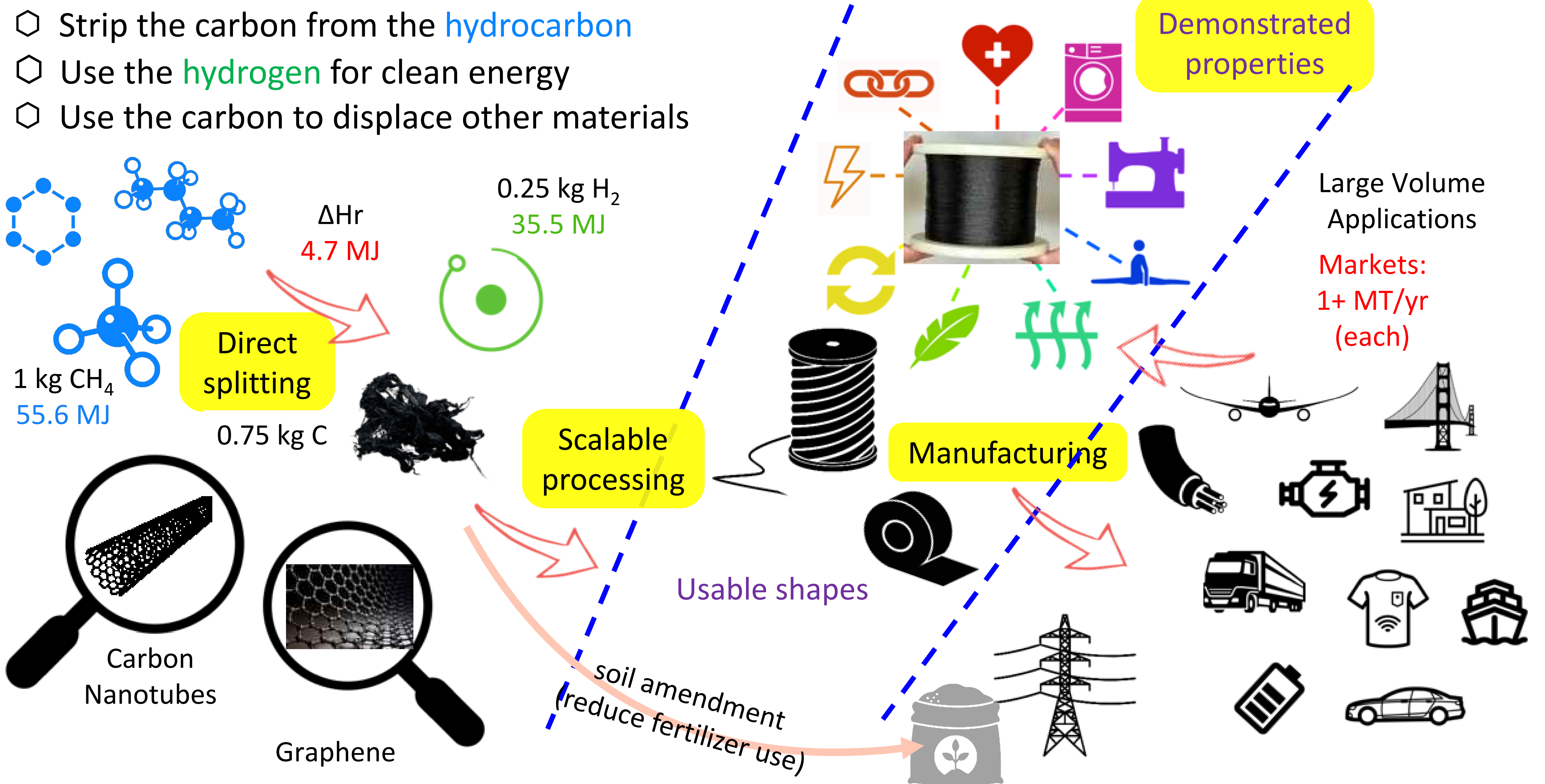


Replacement by carbon:

- Lower energy use
- Eliminate CO_2 emissions

A NEW HYDROCARBON / MATERIAL PATHWAY

- ⬡ Strip the carbon from the hydrocarbon
- ⬡ Use the hydrogen for clean energy
- ⬡ Use the carbon to displace other materials



1 kg CH_4
55.6 MJ

Direct splitting

ΔHr
4.7 MJ

0.25 kg H_2
35.5 MJ

0.75 kg C

Carbon Nanotubes

Graphene

Scalable processing

Usable shapes

soil amendment
(reduce fertilizer use)

Manufacturing

Demonstrated properties

Large Volume Applications

Markets:
1+ MT/yr
(each)

UNSTRUCTURED SOLID CARBON

Dr. Caroline Masiello
Dr. Dan Cohan
Dr. Pedro Alvarez
Rice University

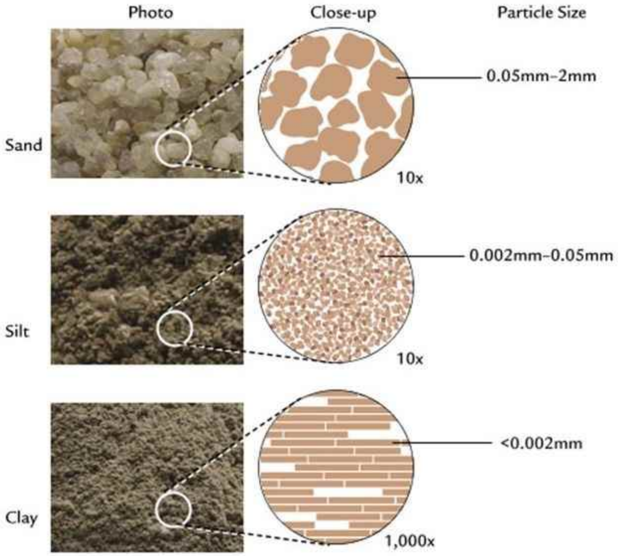
Amending soil with carbon-rich materials

Organic carbon is a key component of soils

Holds nutrients in plant-available forms:
less fertilizer pollution / more fertilizer to crops

Improves soil water properties:
holds more under drought / drains better

Provides microhabitats for microbes that support plant growth.



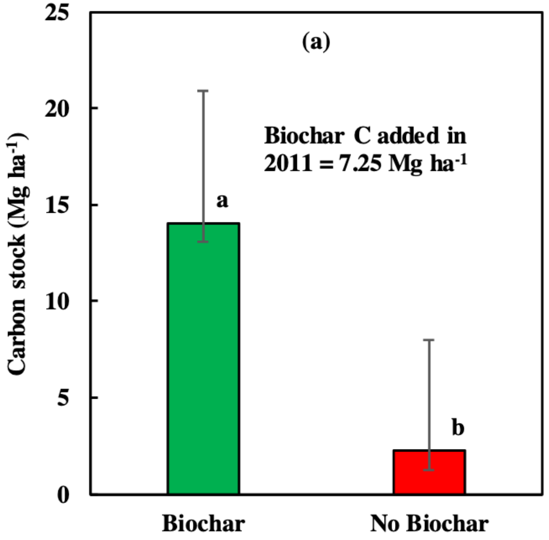
Key properties to improve soils:

- Particle size controls water properties
- Partial charges on organic carbon hold nutrients
- Ability to shuttle electrons

Pyrolytic Carbon potential for soil amendment

Improve soils
&
Create a carbon sink

Some forms of carbon such as biochar can be carbon sinks



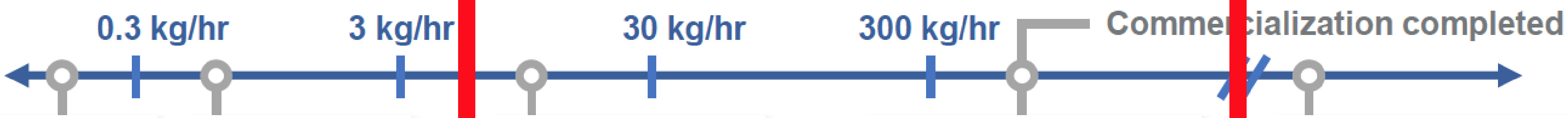
CARBON BLACK VIA METHANE PYROLYSIS

RICE

monolith

2021 Focus

GREEN HYDROGEN PRODUCTION

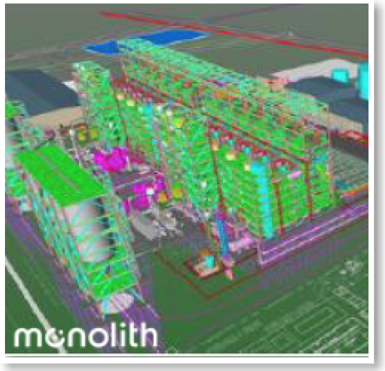


LAB 1
Laboratory Scale
up to 0.3 kg/hr
2016 – 2018

MINES ParisTech
Pilot Scale
0.3 – 2 kg/hr
2018 – Present

Seaport 1
Demonstration Scale
12 – 18 kg/hr
2014 – 2018

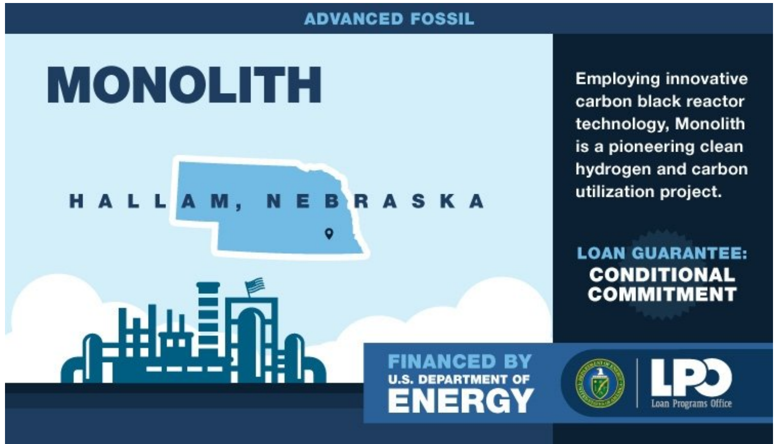
Olive Creek 1
Commercial Scale
540 – 620 kg/hr
2020 – Present



Olive Creek 2
Commercial Scale
6,390 – 7,440 kg/hr
2024

$1 B loan guarantee from DOE

- Olive Creek 2 will produce 0.18 MT/yr carbon black
- ~1.5% of world carbon market
- 0.06 MT/yr Hydrogen
- Avoid and displace ~1 MT/yr CO_2 emissions



ADVANCED FOSSIL

MONOLITH

HALLAM, NEBRASKA

Employing innovative carbon black reactor technology, Monolith is a pioneering clean hydrogen and carbon utilization project.

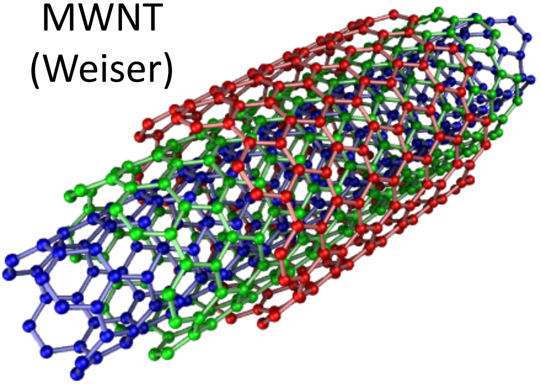
LOAN GUARANTEE:
CONDITIONAL COMMITMENT

FINANCED BY
U.S. DEPARTMENT OF
ENERGY

LPO
Loan Programs Office

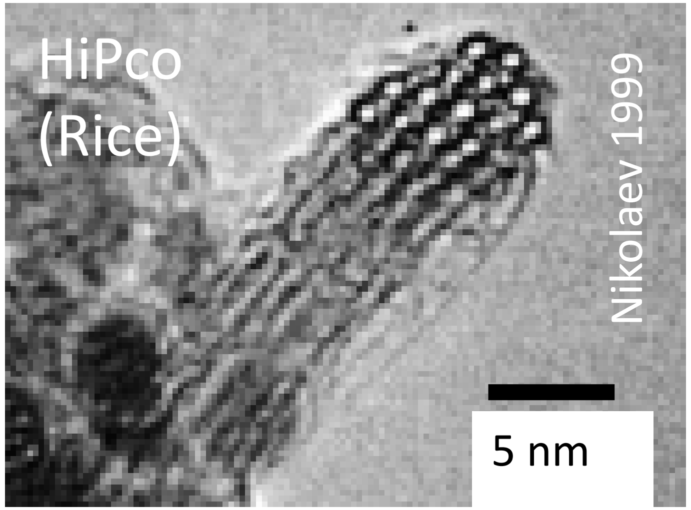
EARLY HISTORY OF CARBON NANOTUBES

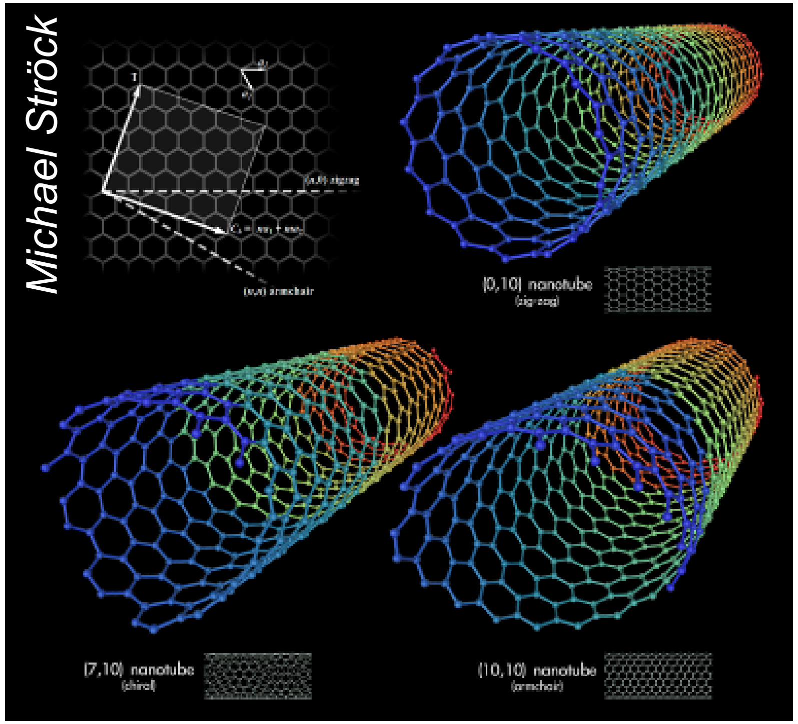
MWNT
(Weiser)



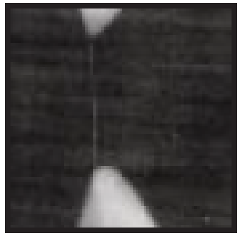
EARLY DEVELOPMENTS IN CNT MATERIALS

- CNT discovery in 1991 (Iijima)
- By mid-1990s, it becomes clear that CNTs are a material class
- Mid-1990s: focus on CNTs because of applications
- Strength ~ 30-40 Gpa (~100x steel)
- Elec. Cond ~100 MS/m (~2x Copper)
- Thermal Cond ~ 3000 W/ m K (~10x Aluminum)





- Large-scale (~10 g) production attained by ~1995 (Smalley)
- Very slow application development
  - Few application articles by ~2000
- Making macroscale materials very difficult
  - No control on liquid phases
  - No control on macroscopic structures
  - No control on macroscopic properties
- Late 1990s hype followed by late 2000s disillusionment



Superstrong Materials 0

Nanotube stress test

Feasibility Ratings
0 = Science Fiction
2 = Demonstrated
4 = Ready for Market

Scientific American, December 2000

CARBON NANOTUBES NOW

RICE

Vibrant Ecosystem of Companies & Labs

This future is already here!
(just not very evenly distributed…)

DexMat
HIGH PERFORMANCE CNT PRODUCTS

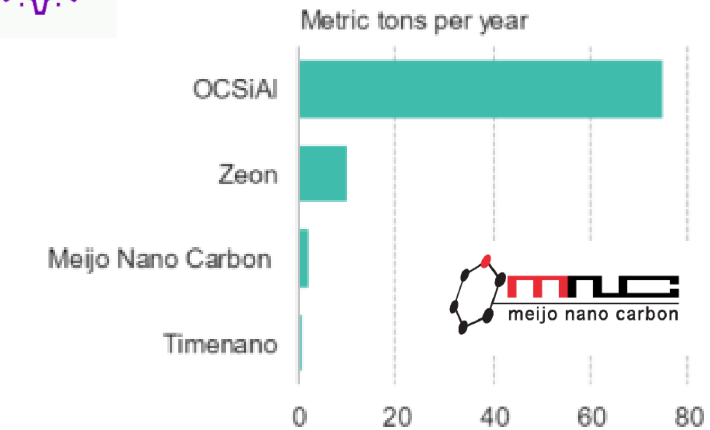
COI: MP co-founded DexMat

CNT braided rope

CNT film

Galvorn

World production of carbon nanotubes (fiber-grade)



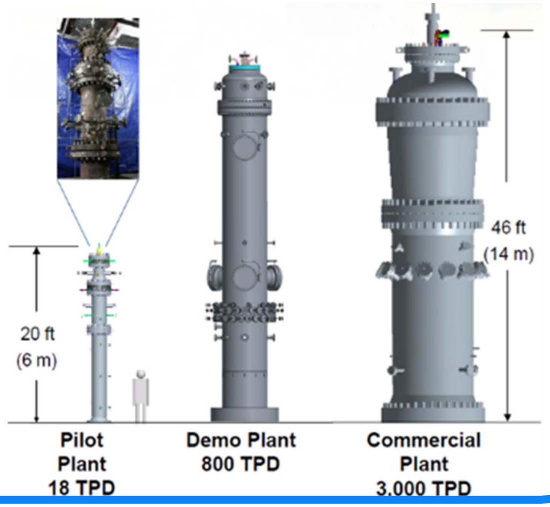
Source: BloombergNEF, NEDO, Company websites.

~120 tons / year in 2021

HUNTSMAN

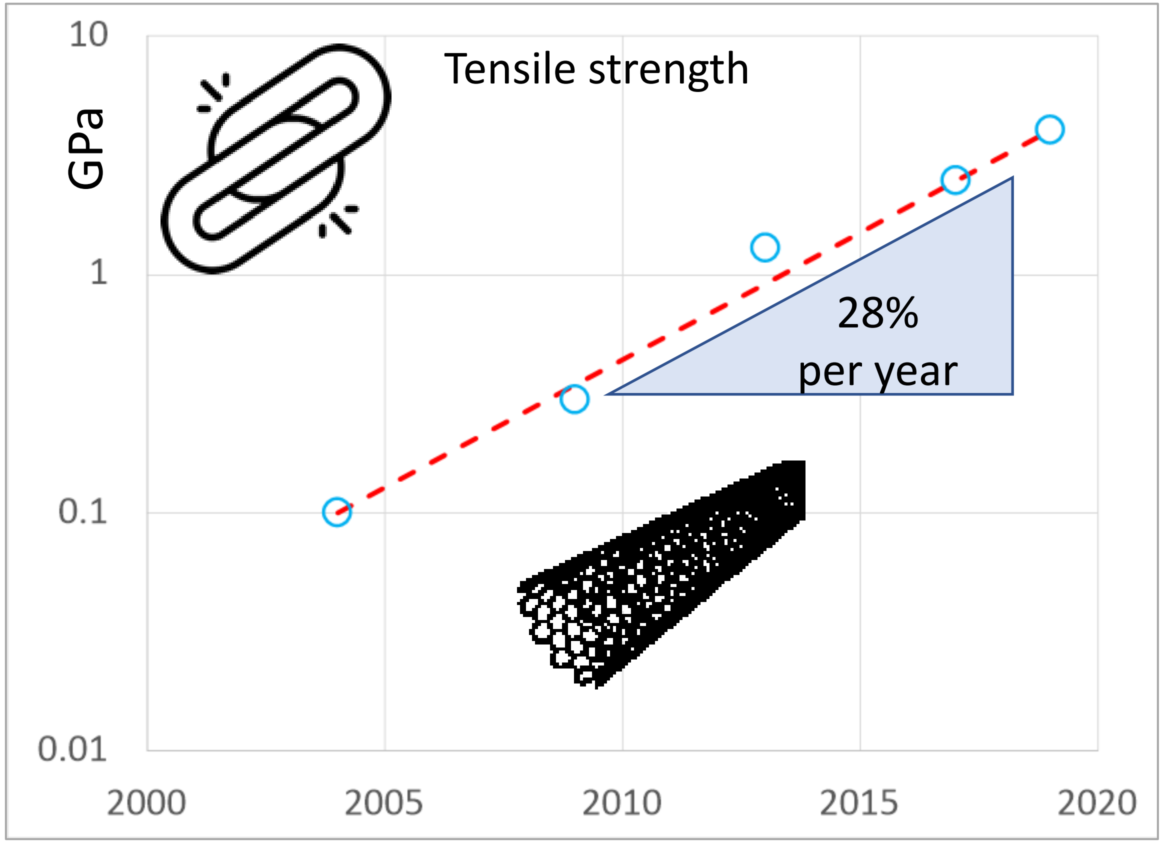
nanocomp
TECHNOLOGIES, INC.
A Huntsman Company

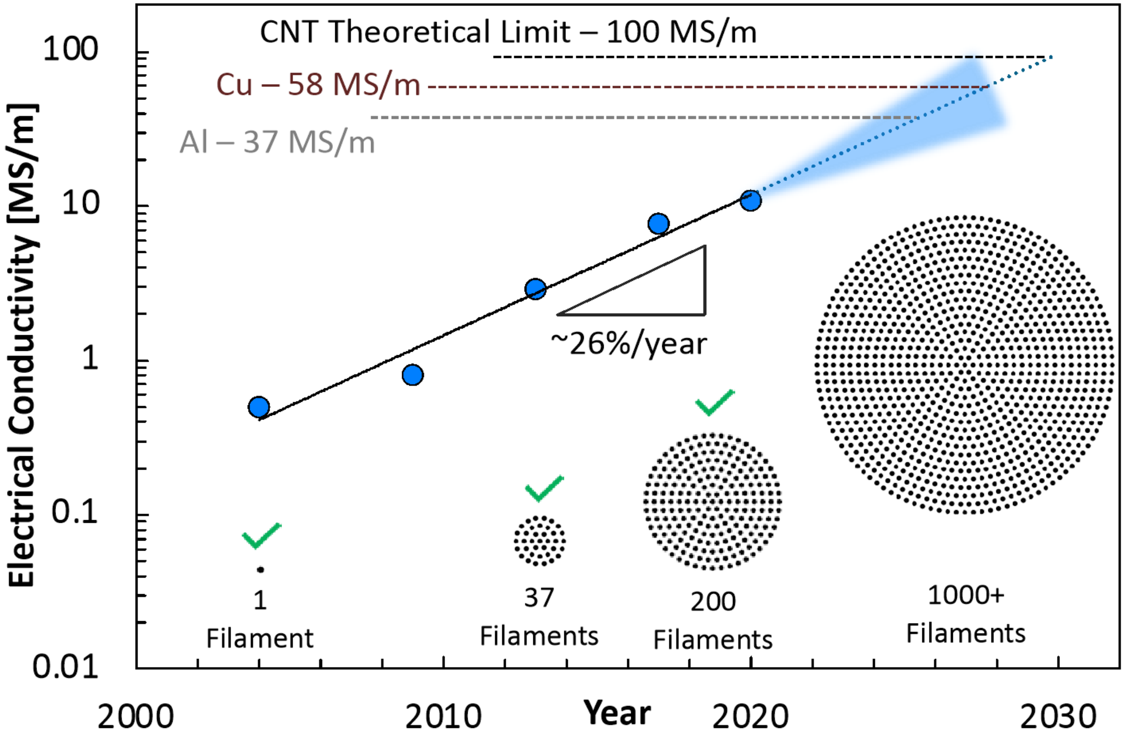
Miralon

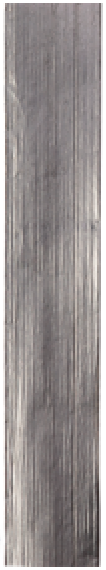


No longer a laboratory curiosity

PROPERTIES DEVELOPMENT: LEARNING CURVES







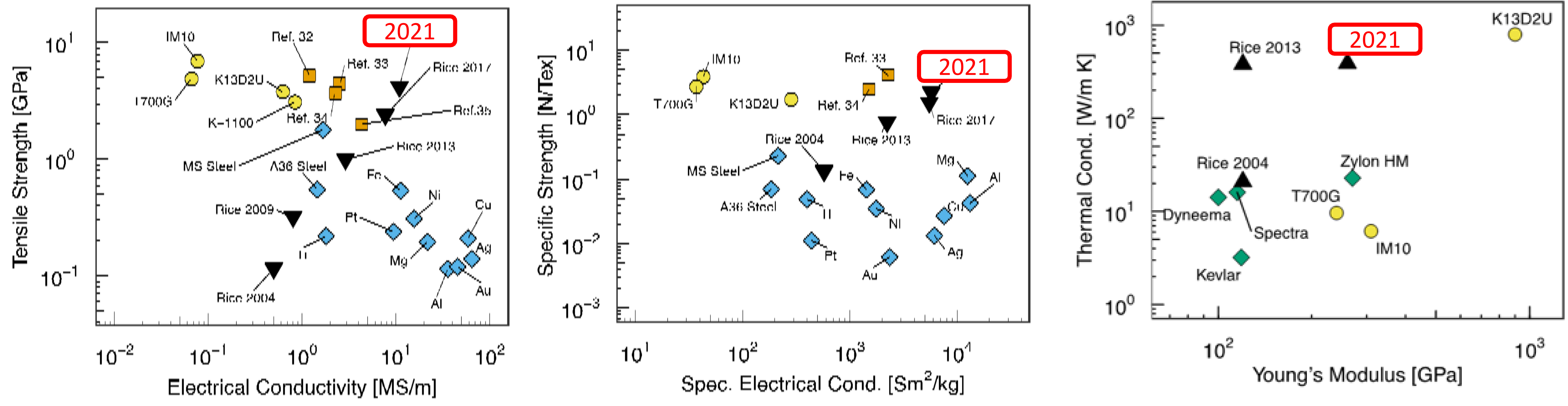
DexMat
HIGH PERFORMANCE
CNT PRODUCTS

Galvorn

- Very steep property improvement
  - Doubling every 3 years
- Available in km-length, mm-diameter
  - wires, tapes, fabrics (Galvorn)
- R&D is continuing

DISPLACEMENT OF METALS & CARBON FIBERS

L. W. Taylor, O. S. Dewey, M. Pasquali, et al., *Carbon*, 2021



- ● Carbon Fiber
- ■ Direct Spun CNT
- ◆ Metals
- ▲ Polymers
- ▼ Solution Spun CNT

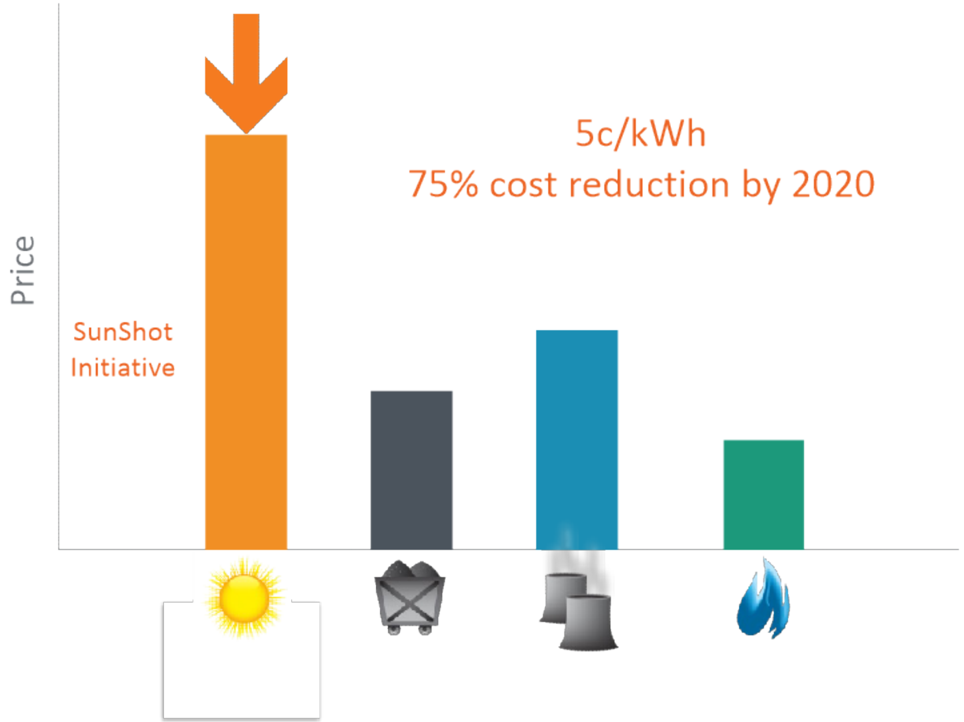
- ⬡ high strength (~4 GPa) ✓
- ⬡ high stiffness (~250 GPa) ✓
- ⬡ high electrical conductivity (~11 MS/m) ✓
- ⬡ high thermal conductivity (~400 W/ m K) ✓
- ⬡ low coefficient of thermal expansion ✓
- ⬡ earth-abundant content ✓
- ⬡ recyclable and safe for EOL ✓

- ⬡ low density (~ 1800 kg/m^3) ✓
- ⬡ high ampacity ✓
- ⬡ corrosion-resistant (carbon) ✓
- ⬡ high bending fatigue strength ✓
- ⬡ high operating temperature ✓
- ⬡ high flexibility ✓

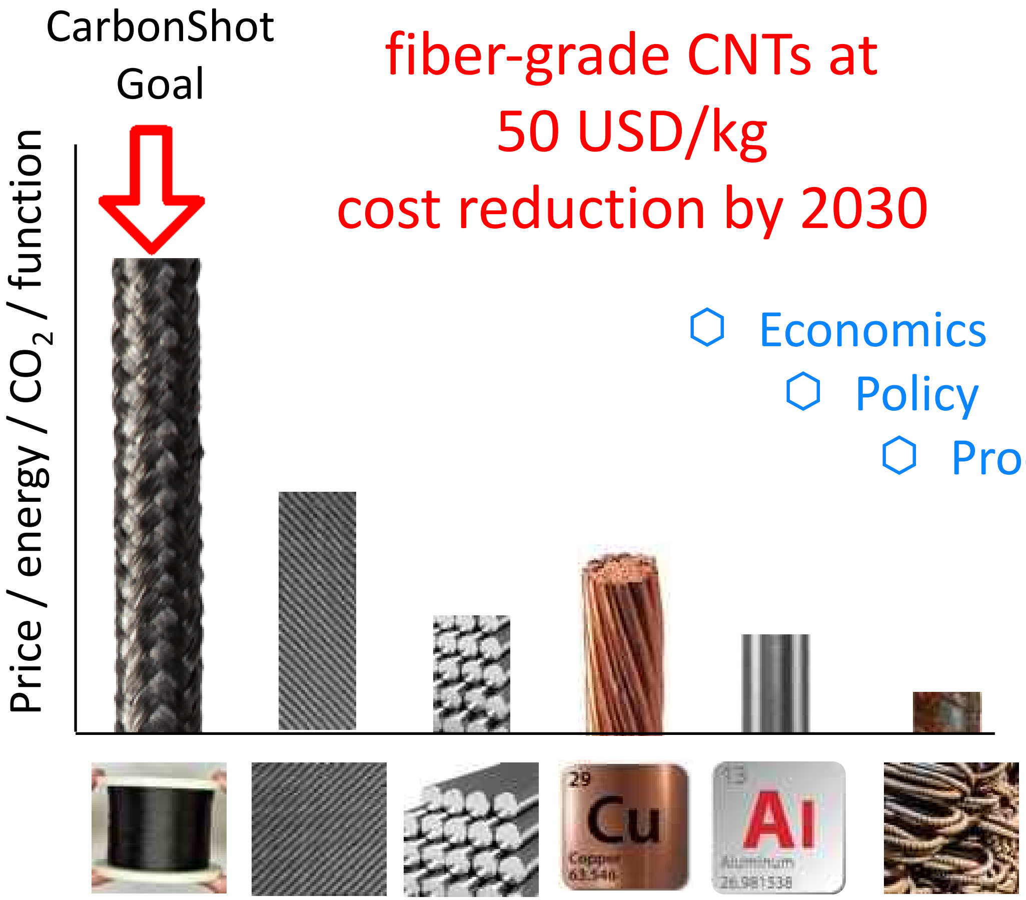
WHAT NEEDS TO HAPPEN?

- From solar energy playbook
- Attain cost-parity with incumbents

SunShot Goal



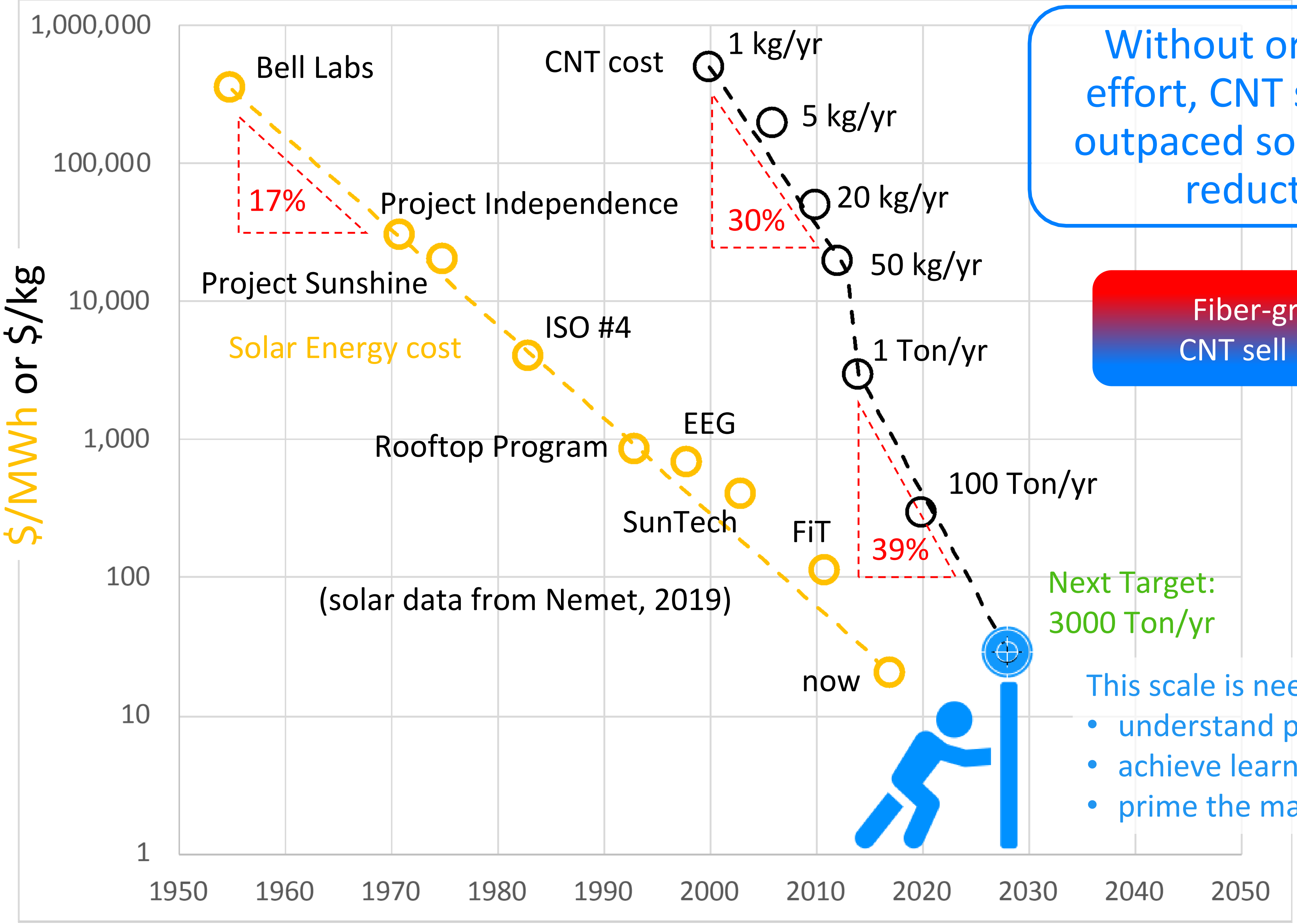
- Carbon Materials must achieve cost parity with incumbents
- Total cost of ownership/LCA at product level
- Embodied energy, CO_2



fiber-grade CNTs at
50 USD/kg
cost reduction by 2030

- Economics
  - Policy
    - Product design

COST AND COST REDUCTION: COMPARISON TO SOLAR



(solar data from Nemet, 2019)

Without organized effort, CNT synthesis outpaced solar in cost reduction

Fiber-grade
CNT sell price

Next Target:
3000 Ton/yr

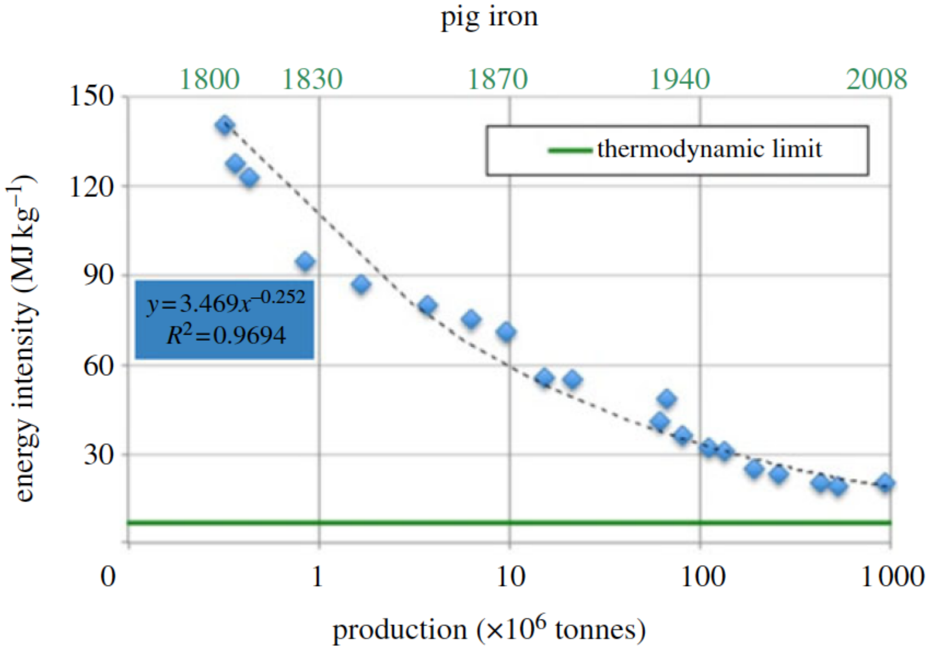
This scale is needed to:

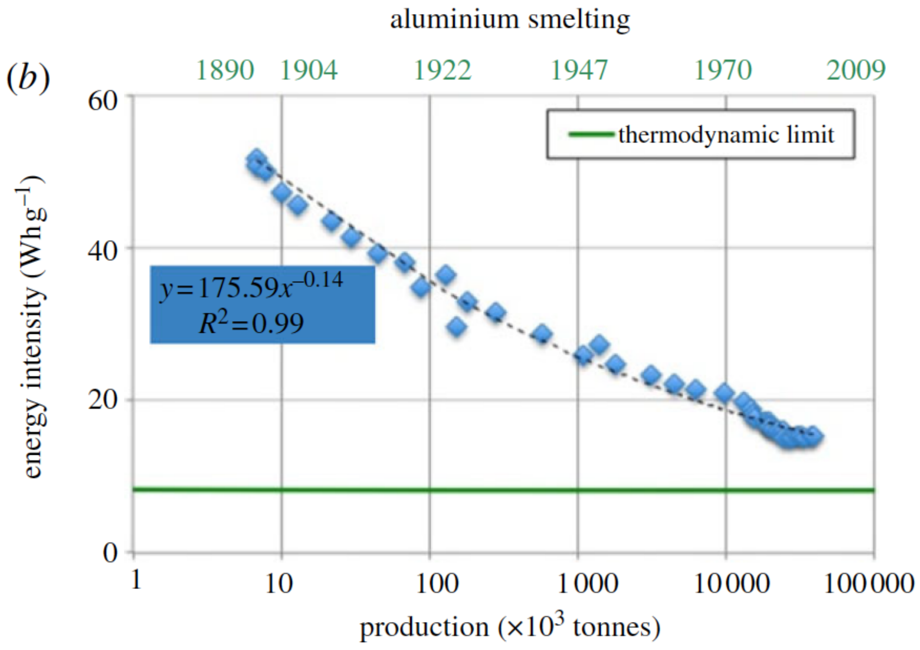
- understand process scaling
- achieve learning-by-doing
- prime the market

HISTORICAL EXAMPLES OF MATERIAL COST REDUCTION

- Steel and aluminum are great examples
- Both were known for decades/centuries before mass scaling
- Considered specialty (even used for jewelry)
- Introduced as top-performing materials
- Gradually became commodities
- Material energy intensity drops with production scale
- By itself, elapsed time is not important
- Cost follows energy intensity
- Fast development and introduction of products is critical

Can we use science
to lower cost faster?

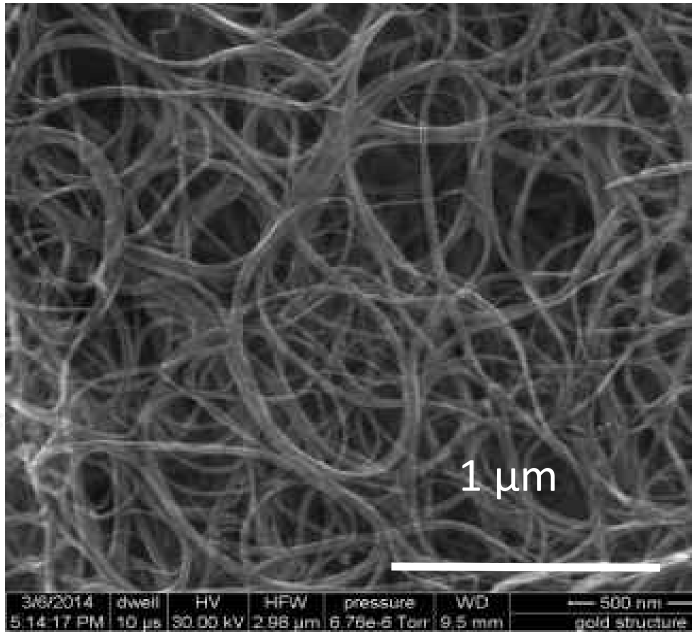




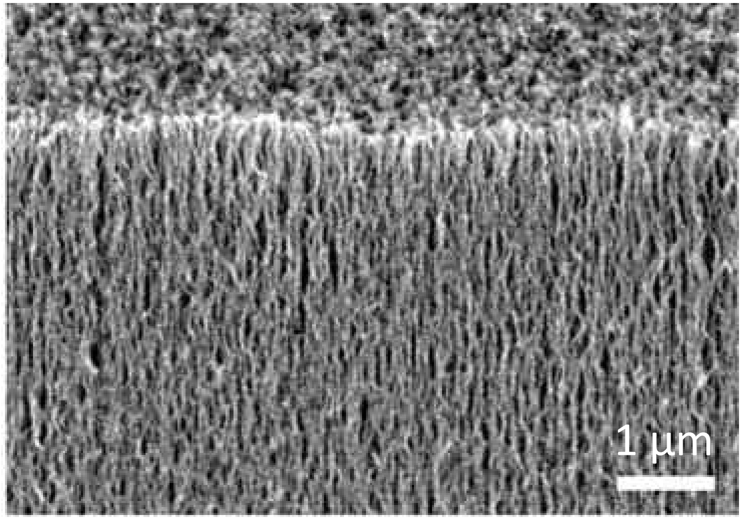
Gutowski, et al, *Phil Trans R Soc A,* 2013

HOW ARE CNTs MADE?

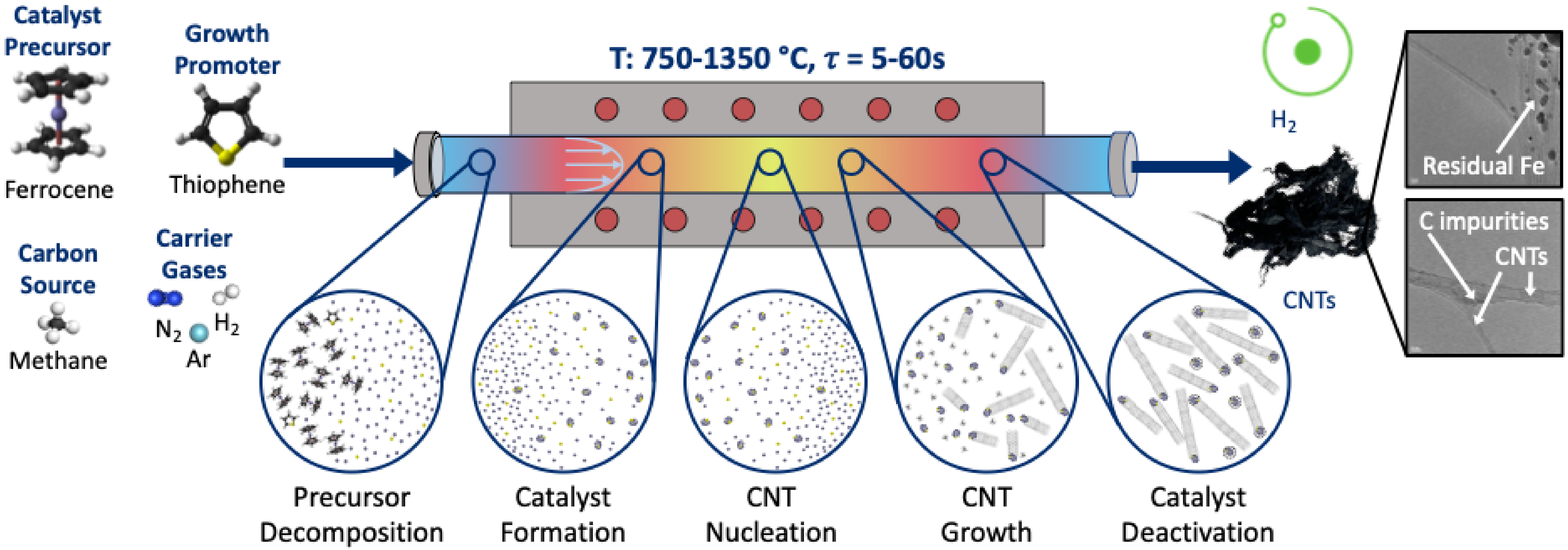
- Carbon source (graphite, CO, hydrocarbons)
- Metal catalyst (1-5 nm particles)
- Dilution (hydrogen, nitrogen)
- Moderate temperature (750-1300 C)
- Various reactor configurations
    - Fixed/floating bed, unsupported catalyst (no support), surface-supported
- Up to ~2015, no attention to efficiency
- Up to ~2020, low reactor understanding
- 2018-2018
    - Rice, Shell, and ARPA-E launch a focused program on understanding CNT reactors
    - Other participants (Huntsman, Stanford, U Cambridge, Politecnico di Milano…)
    - Reactor data, process/plant modeling
    - Fully-integrated program (methane to fibers)



Hata et al, Science 2004

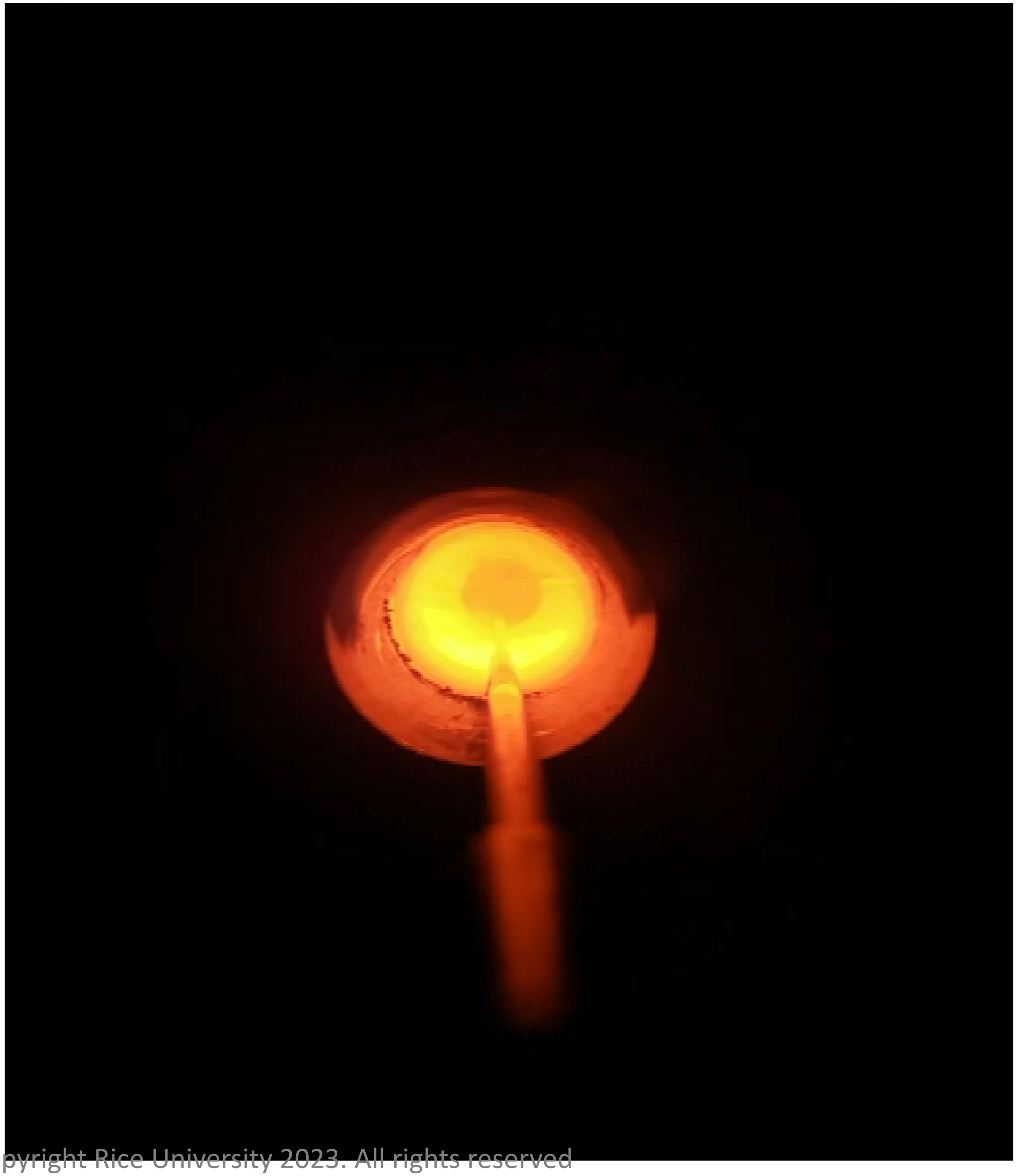


CNT SYNTHESIS VIA CONTINUOUS FLOW REACTORS



- Largely treated as “black boxes” so far
- Reactor/reaction efficiency
- Catalyst utilization
- Selectivity to CNTs

CNT SYNTHESIS: NEW LEARNING CURVE

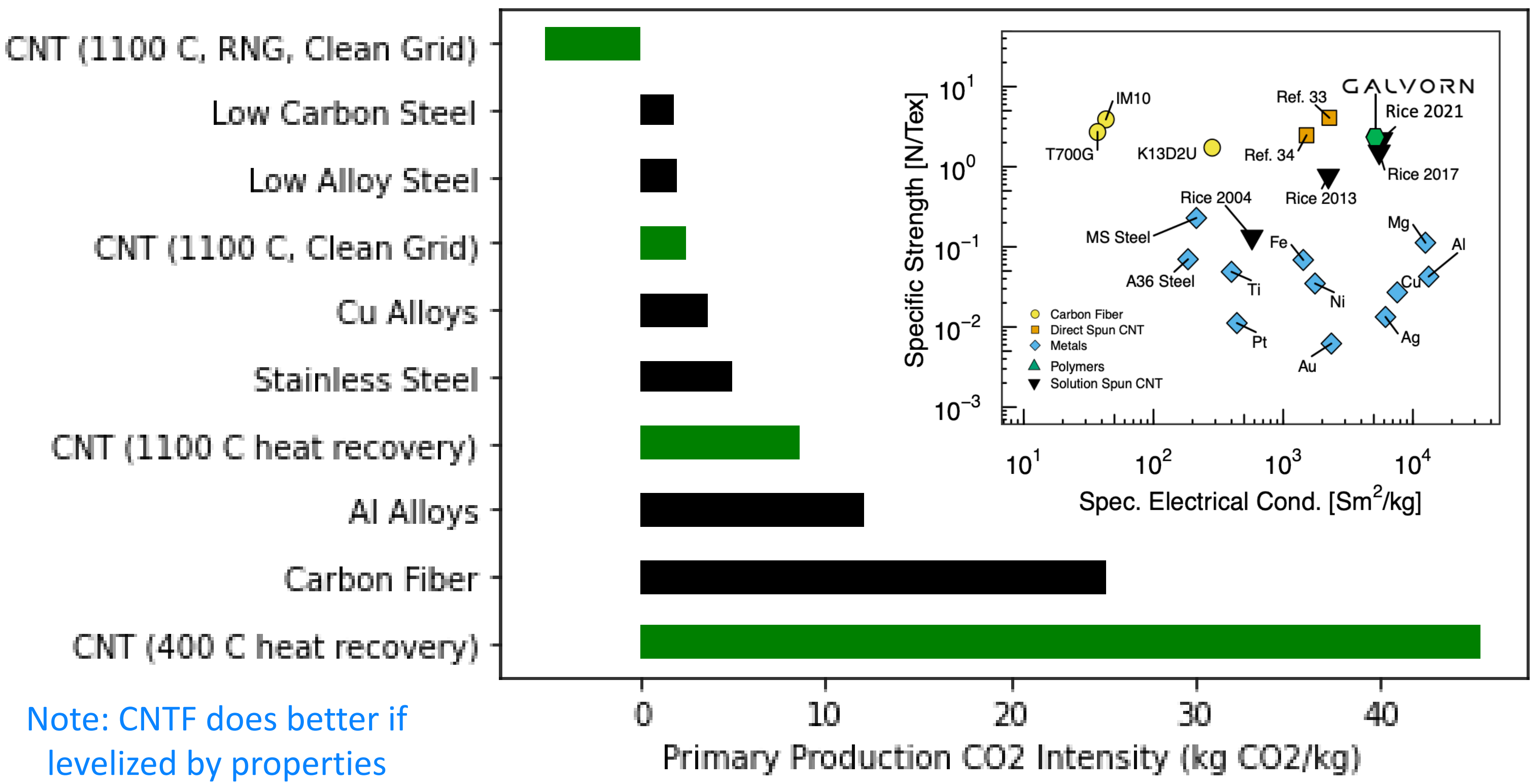


- CNTs grown from methane
- Conversion from 0.05% (2019) to ~30% (now)
- Selectivity from ~70% to > 90%
- Continuous production, inexpensive catalyst & dilution gases
- Hydrogen co-production proven
- Embodied energy below 200 MJ/kg
  - Better than carbon fibers, aluminum
  - Could drop another 10x with further intensification

Carbon nanotubes at reactor exit

- Proven at ~5 kg/yr
- ~1,000x cost reduction
  - Ready for demo-scale
- Product considerations:
  - High-quality maintained
  - Fiber-grade CNTs
    - High strength
    - High electrical cond.
    - High thermal cond.

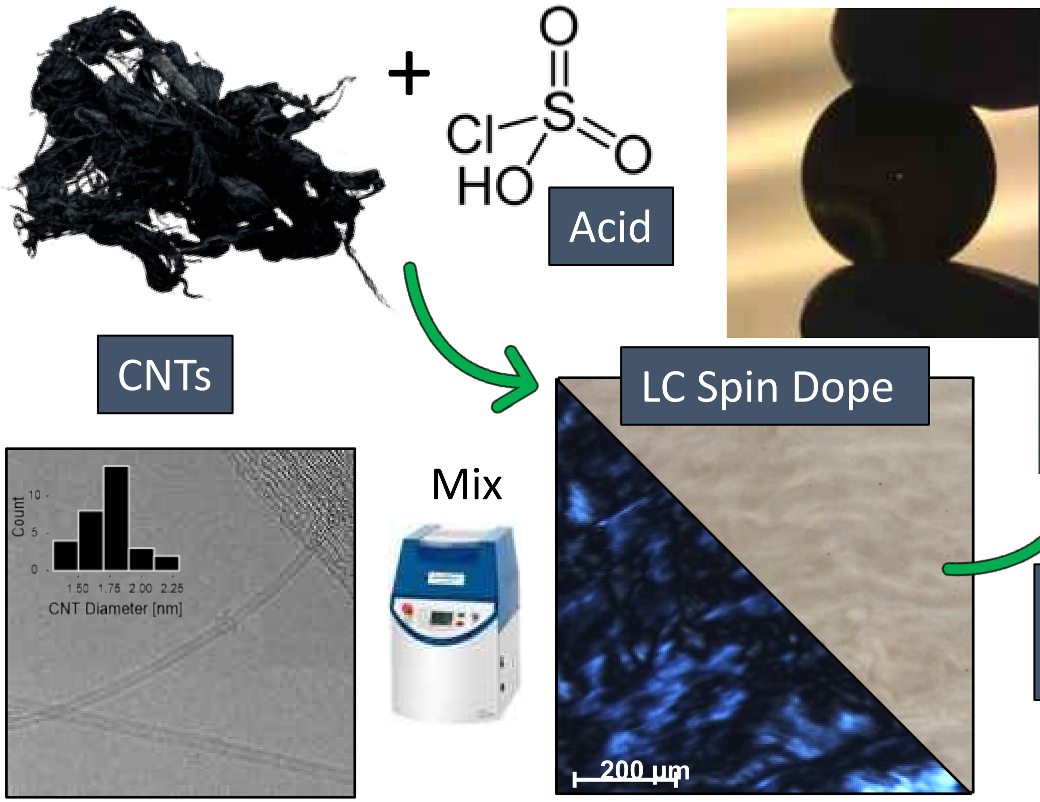
CARBON-NEGATIVE MATERIALS!

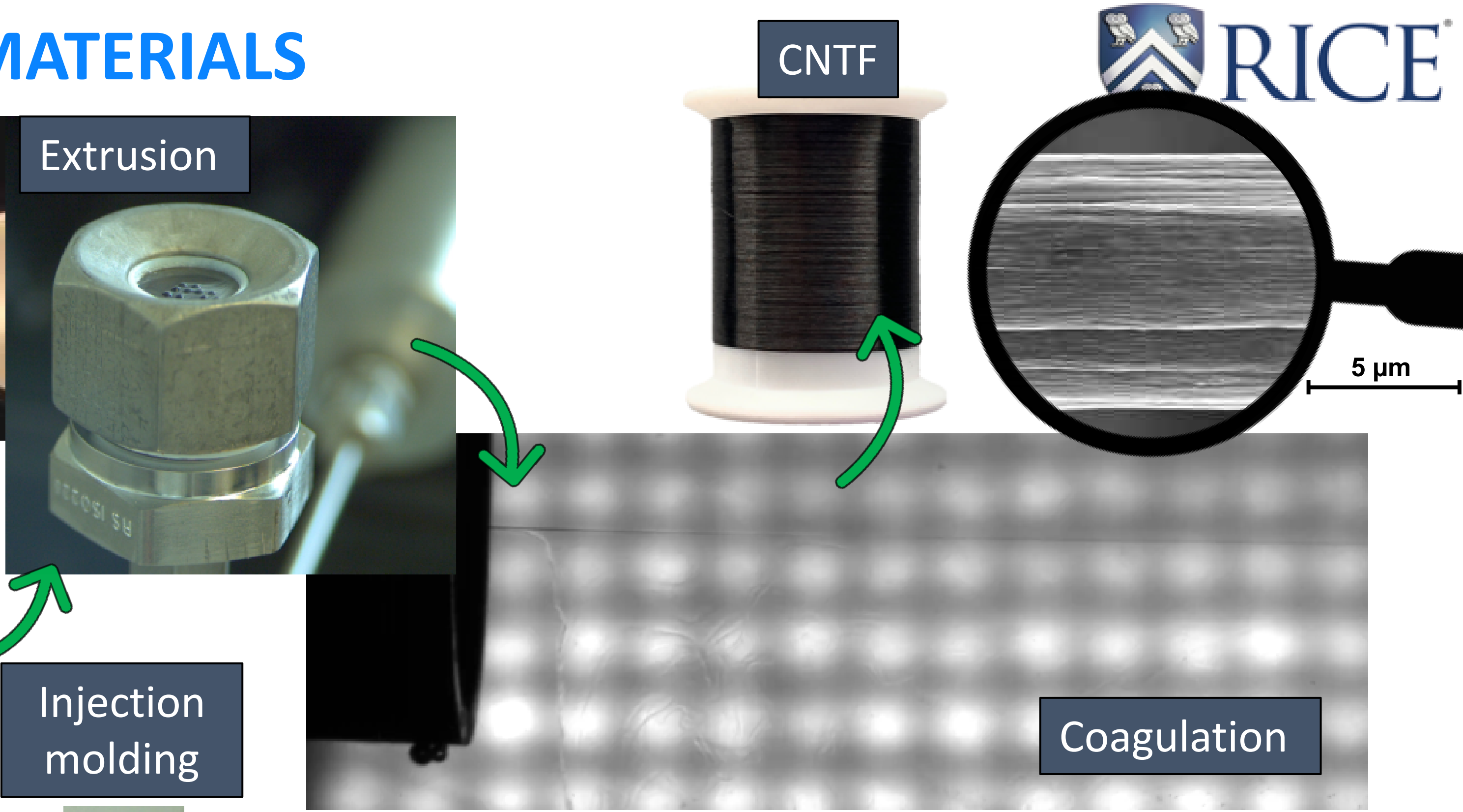


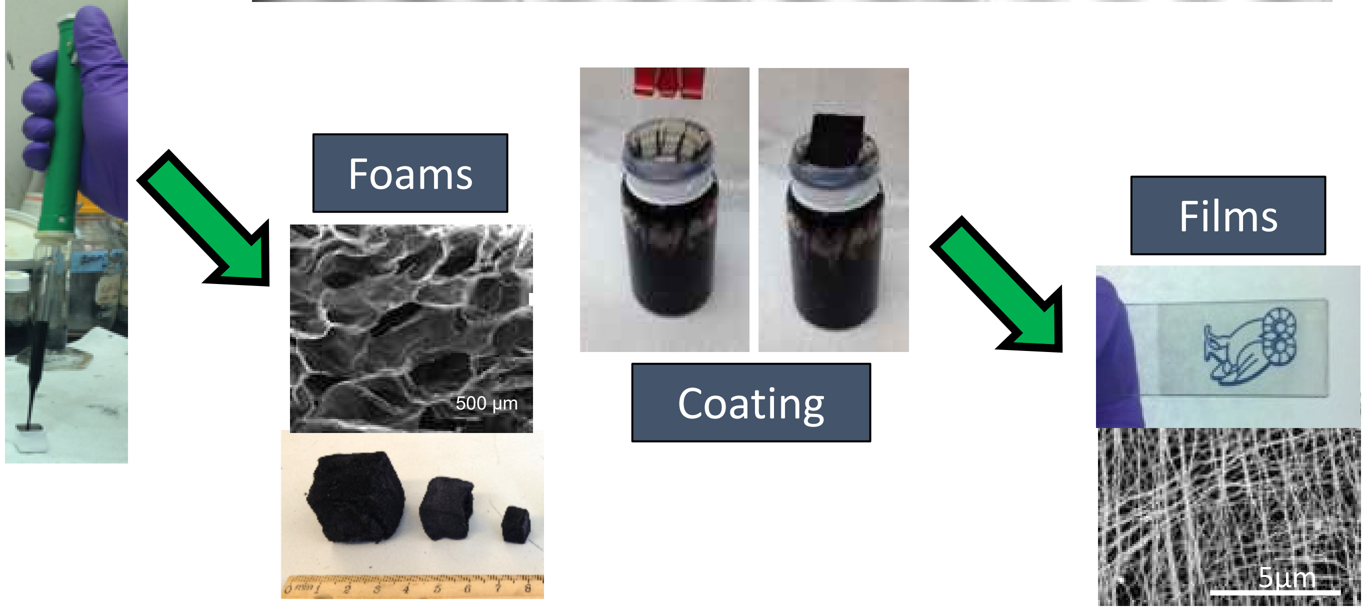
Note: CNTF does better if levelized by properties

- On US grid and with heat integration, CNTs are competitive with Carbon Fibers & Aluminum
- On clean grid, they are cleaner than industrial metals
- When using renewable natural gas, they are carbon negative!

FROM CNT POWDER TO MACRO MATERIALS







- Use liquid crystal (LC) ordering and flow to create order
- Lock in order and densify with coagulant
- Solution processing extends to other geometries

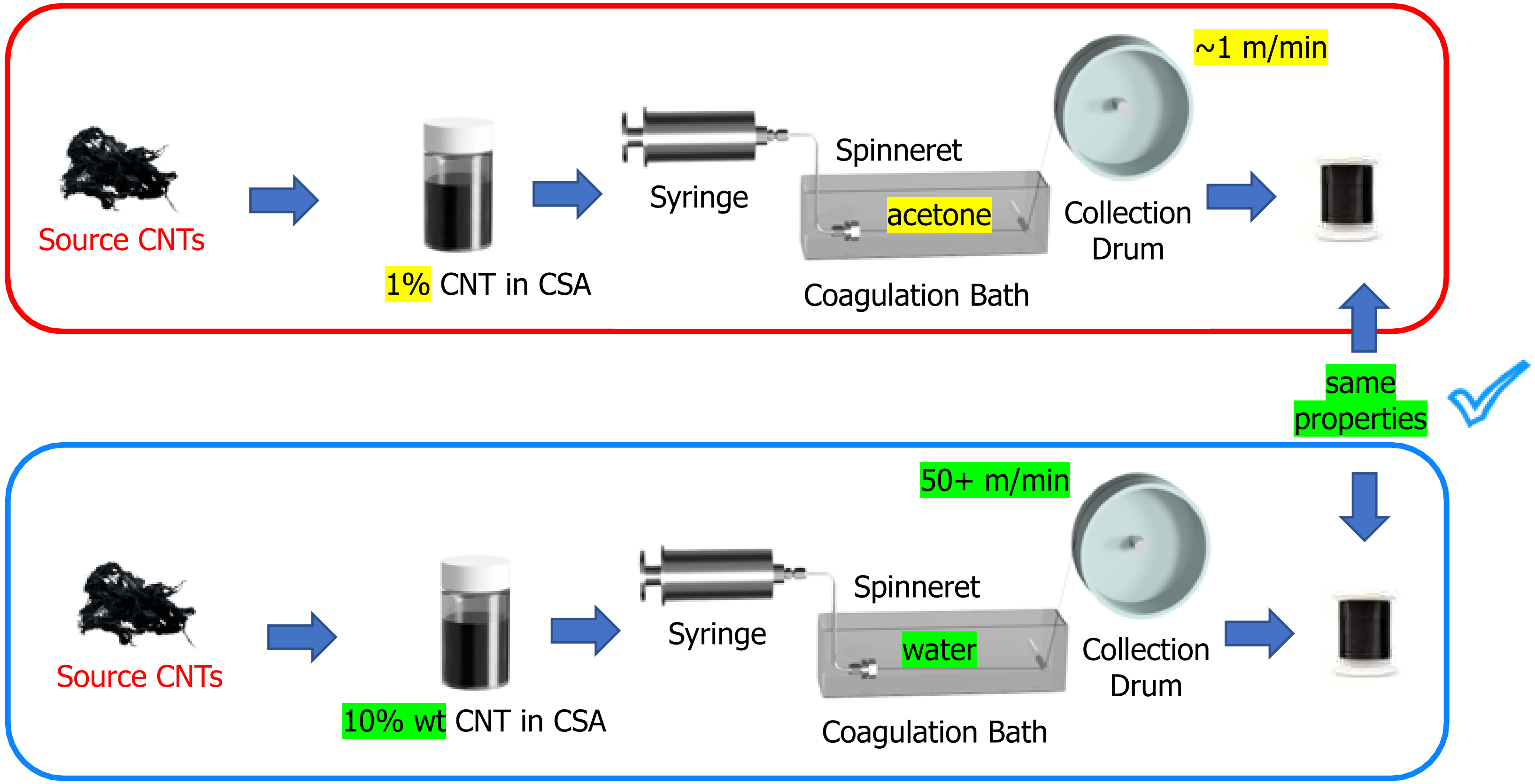
FIBER SPINNING PROCESS INTENSIFICATION

Conventional spinning

- Slow (~1 m/min)
- Low CNT concentration
  - 0.5% to 2%
- Uses organics (acetone)
  - Cost
  - CO_2 footprint
- End-of-life questions

GS-spinning

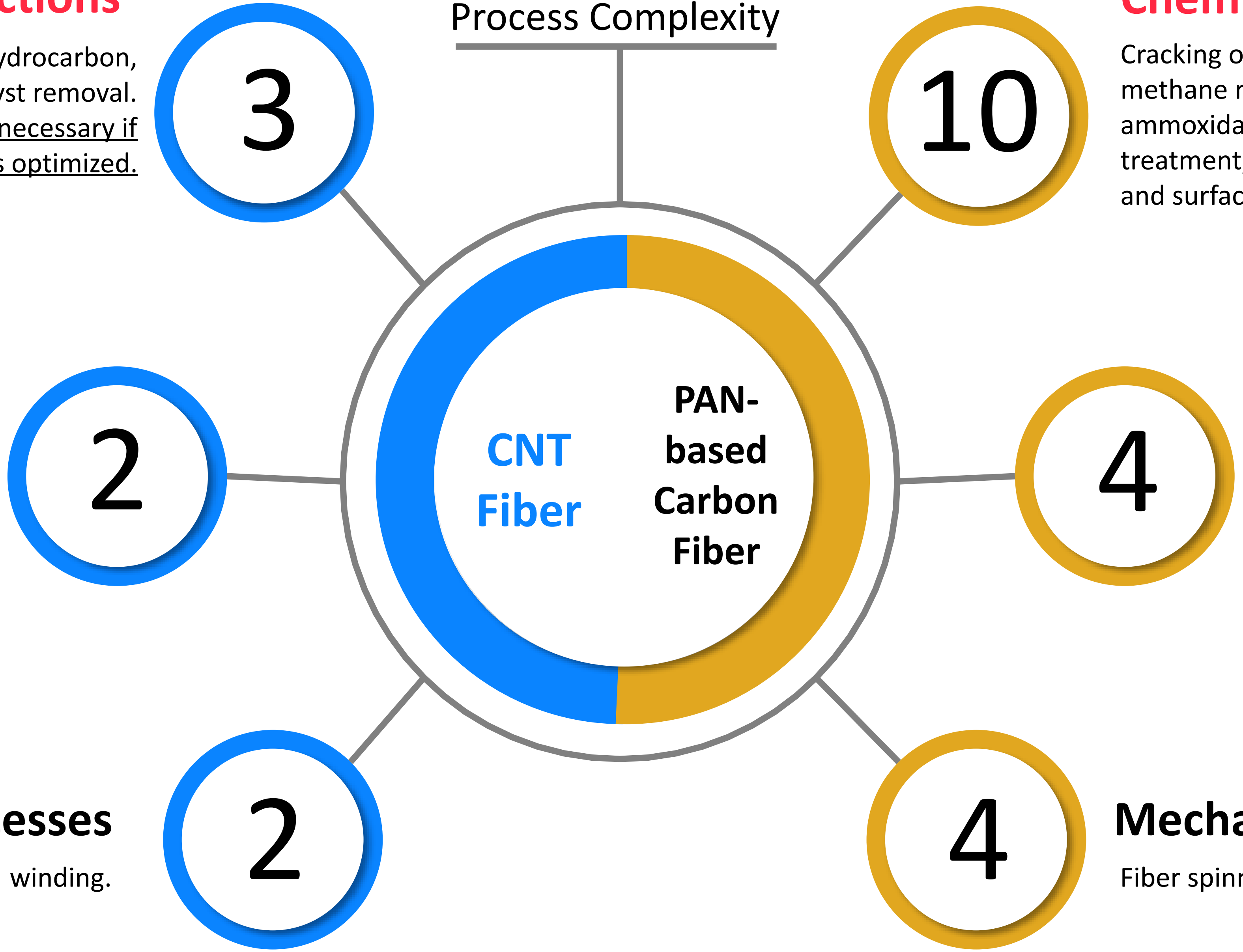
- Fast (30+ m/min)
- High CNT concentration
  - 10%, maybe higher
- No organics
- Full recyclability demonstrated



- Over 500x reduction in variable costs
- Production much simpler than current carbon fibers
- Fits existing industrial platform for scale-up

CNT FIBERS vs PAN-BASED CARBON FIBERS

Comparative Process Complexity



Chemical Reactions

Splitting of the hydrocarbon, purification*, catalyst removal.

*Purification may not be necessary if reaction is optimized.

Phase Changes

Dissolution of CNT in CSA or oleum; coagulation in water.

Mechanical Processes

Fiber spinning and winding.

Chemical Reactions

Cracking of naphtha or propane, steam methane reforming, Haber-Bosch process, ammoxidation, PAN polymerization, pre-treatment, oxidation, 2x carbonization, and surface treatments.

Phase Changes

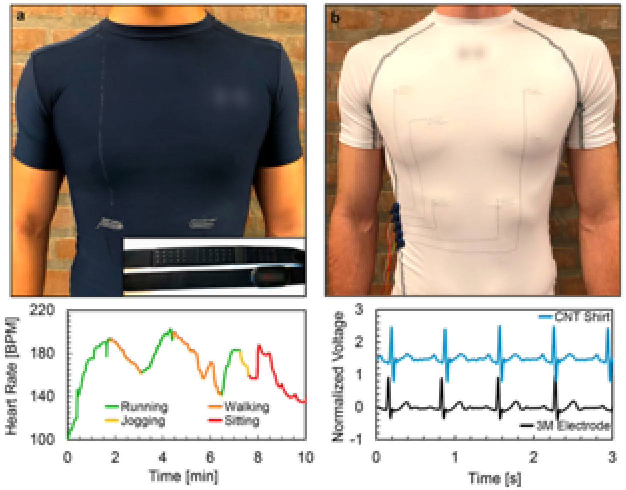
Separation of propane or naphtha from natural gas or oil, dissolution of PAN in DMSO, DMF, or DMAc, coagulation in methanol, and washes.

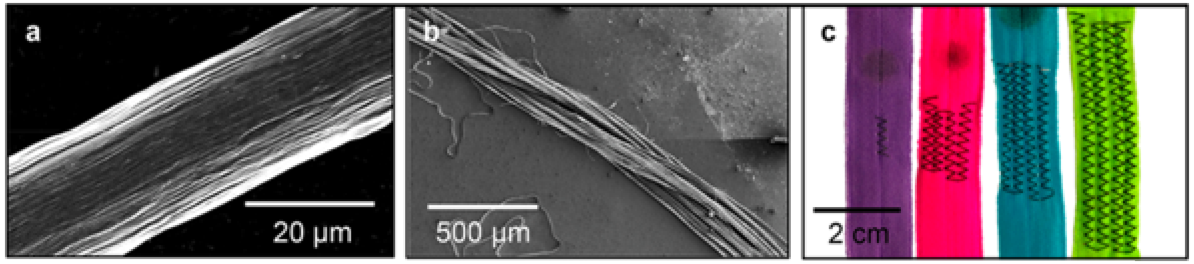
Mechanical Processes

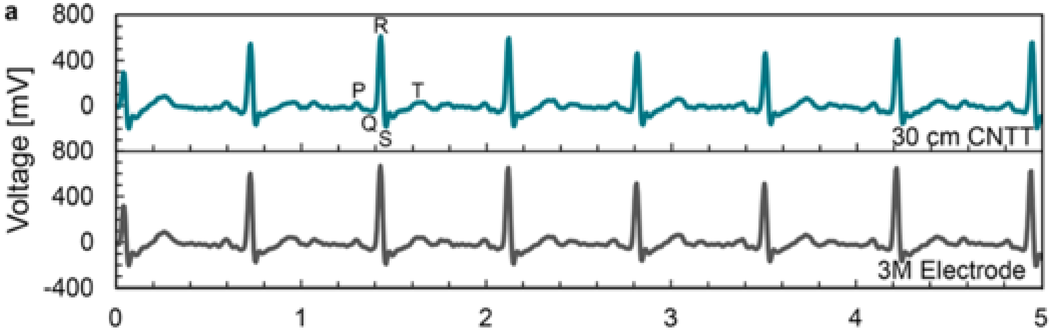
Fiber spinning, 2x winding, and sizing.

APPLICATIONS OF STRONG, FLEXIBLE CNT CONDUCTORS

- Combination of softness and mechanical/electrical properties is great for wearable applications
- Comfortable, reusable sensors for the wrist
- Sewn in sensors for heart-rate-monitoring T-shirt







Taylor, Lauren W., Steven M. Williams, J. Stephen Yan, Oliver S. Dewey, Flavia Vitale, and Matteo Pasquali. "Washable, Sewable, All-Carbon Electrodes and Signal Wires for Electronic Clothing." *Nano Letters* 21, no. 17 (September 8, 2021): 7093–99. https://doi.org/10.1021/acs.nanolett.1c01039.

DESIGN CHANGES AT DEVICE ARCHITECTURE LEVEL

Ponte di Tiberio (Rimini, Italy)

Golden Gate Bridge (San Francisco)

ARCH BRIDGE: COMPRESSION

$$\text{Material property} = \frac{\text{compressive strength}}{\text{density}}$$

$$\text{Istrian stone} = \frac{171\ \text{MPa}}{2690\ \text{kg/m}^3} \approx 60{,}000\ \text{m}^2/\text{s}^2$$

$$\text{Steel} = \frac{152\ \text{MPa}}{7850\ \text{kg/m}^3} \approx 20{,}000\ \text{m}^2/\text{s}^2$$

SUSPENSION BRIDGE: TENSION

$$\text{Material property} = \frac{\text{tensile strength}}{\text{density}}$$

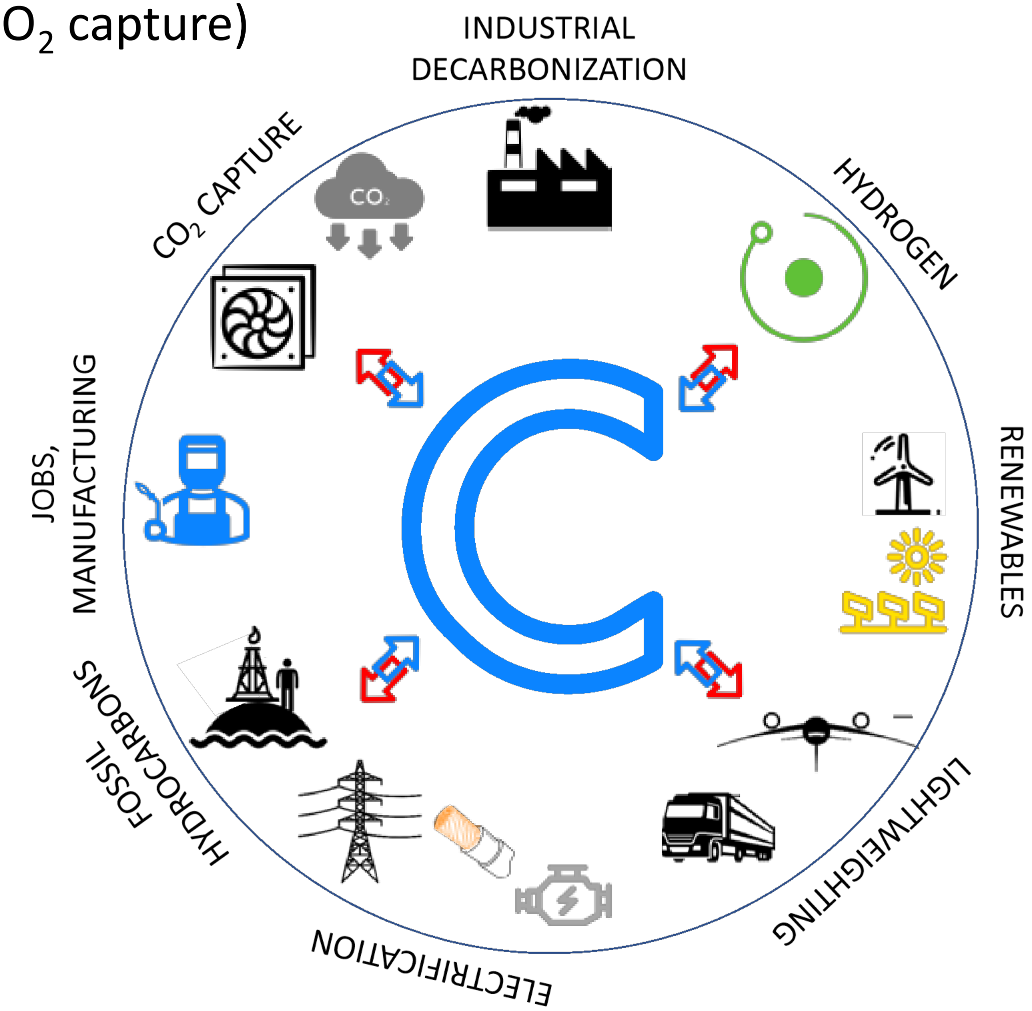
$$\text{Istrian stone} = \frac{16.7\ \text{MPa}}{2690\ \text{kg/m}^3} \approx 6{,}200\ \text{m}^2/\text{s}^2$$

$$\text{Steel} = \frac{550\ \text{MPa}}{7850\ \text{kg/m}^3} \approx 70{,}000\ \text{m}^2/\text{s}^2$$

- New properties can enable architectural redesign
- Building a new industry will require coordination

CLIMATE AND ECONOMIC IMPACT AT SCALE

- Material can be CO_2 negative if made from renewable natural gas (-4 kg CO2/kg CNTF)
- Eliminate energy costs of mining and producing industrial metals (~12% of world energy use)
- Eliminate CO_2 emissions from mining and producing industrial metals (~3 GT CO_2/yr)
- Fix and utilize 1+ GT/yr of solid carbon (equivalent to 3.7 GT CO_2 capture)
- Co-produce 300+ MT/yr of Hydrogen
- Preserve fossil hydrocarbon value chains
- Promote fledging renewable hydrocarbon production
- Additional impact in
    - Lightweighting
    - Electrification
    - Material circularity
    - 2-nd generation renewables
- Over 2 T/yr USD Industry
- Secure supply chains
- US manufacturing
- US jobs



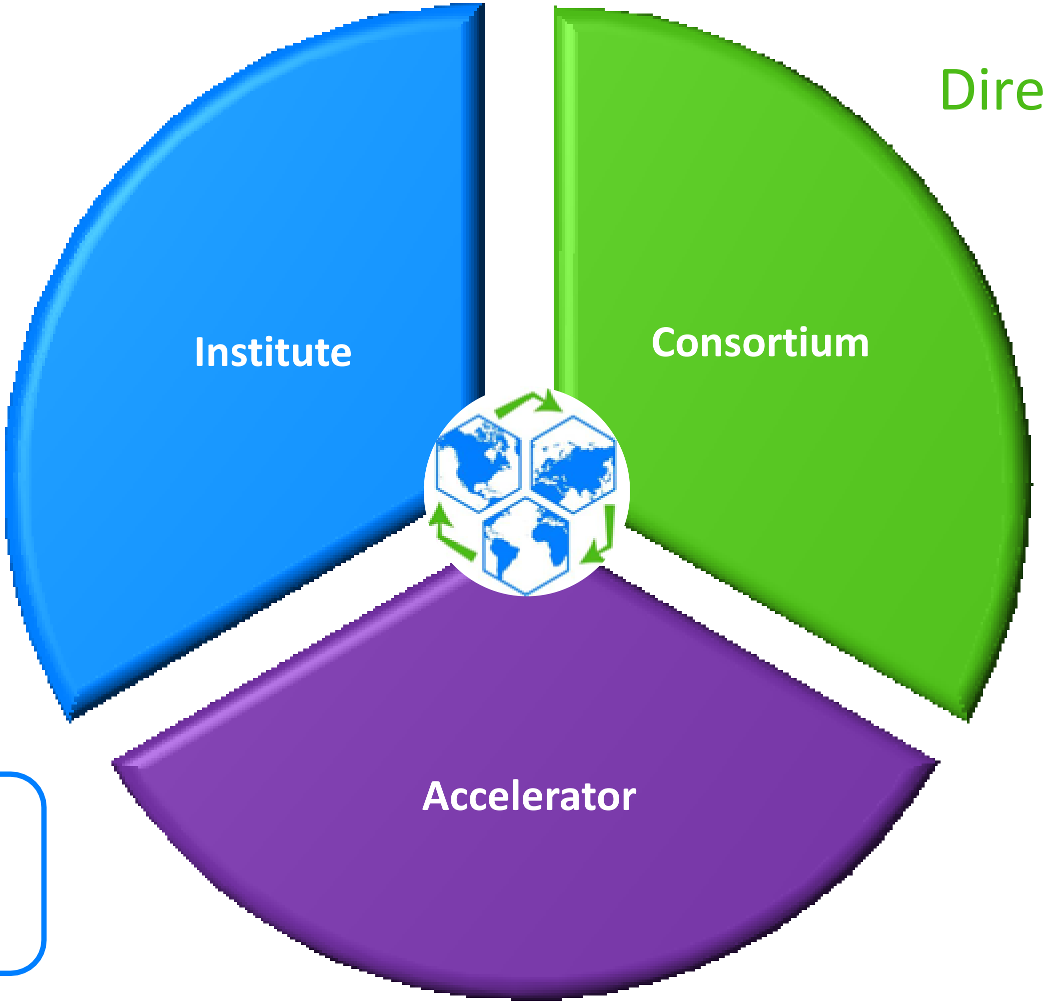
THE CARBON HUB: CREATING A FIELD

carbonhub.rice.edu

Carbon Hub

RICE

Accelerate the emergence of an industry and large markets based on value-added carbon



Direct and fund research in high impact areas

- Engage corporations
- Engage startups
- Organize the innovation ecosystem
- Engage with federal government
  - Agencies
  - National labs
- Engage strategically with other leading climate academic centers

Dr. Marie Contou-Carrere
Executive Director
mncontou@rice.edu

Foster & accelerate the creation of companies in key technology areas

OPEN COLLABORATION MODEL

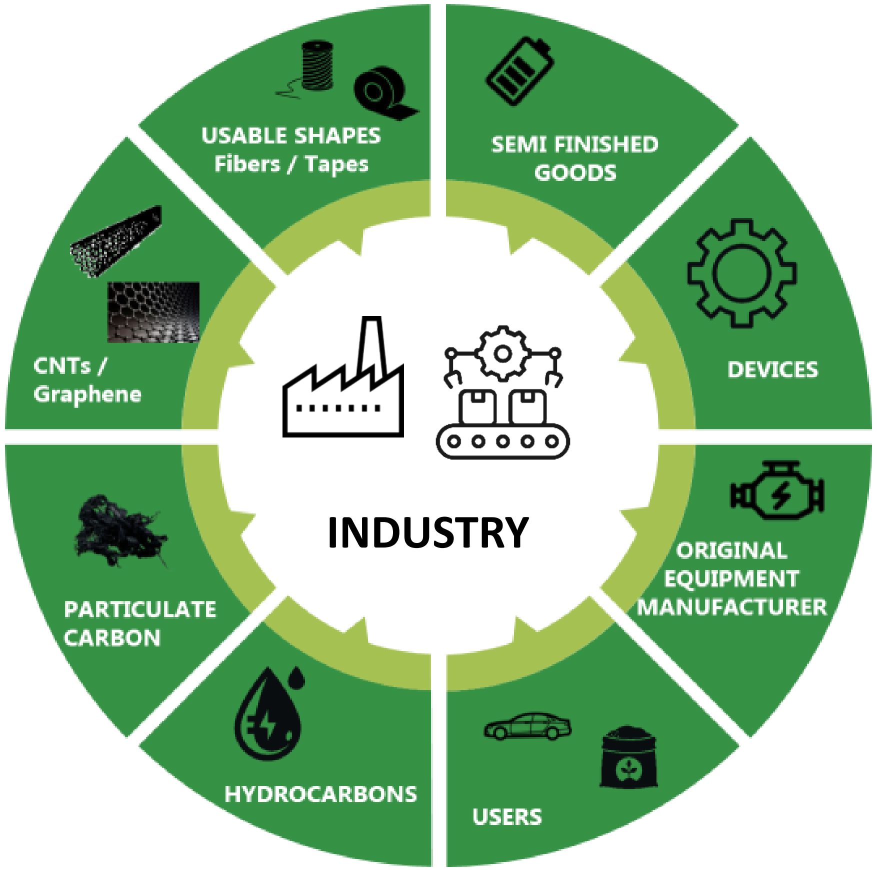
Carbon Hub

RICE

Academia & Federal Labs
Interfacing / Integrating with Industrial R&D

100+ researchers
20+ research organizations

Launched in December 2019


USABLE SHAPES Fibers / Tapes
SEMI FINISHED GOODS
DEVICES
ORIGINAL EQUIPMENT MANUFACTURER
USERS
HYDROCARBONS
PARTICULATE CARBON
CNTs / Graphene
INDUSTRY

أرامكو السعودية saudi aramco

Prysmian Group

سابك sabic

RICE

Mitsubishi Corporation (Americas)

HUNTSMAN
Enriching lives through innovation

Chevron

ExxonMobil

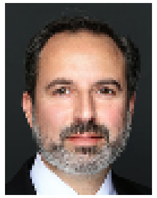
CURRENT PROJECT MAP

Carbon Hub RICE

~$3 MM so far
~$2 MM in contracting

AFRL
Maruyama

University of Dayton Research Institute
Kladitis



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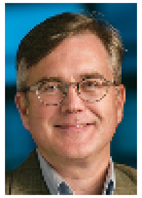
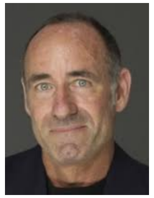
Maboudian

Massachusetts Institute of Technology
Goulthrope

UCDAVIS
UNIVERSITY OF CALIFORNIA
Parikh

Penn
UNIVERSITY of PENNSYLVANIA
Stach





UCSB
UNIVERSITY OF CALIFORNIA
SANTA BARBARA
McFarland


Pasquali


Ajayan


Masiello


Biswal


Wehmeyer


Naik


Castellon

International collaborators

UNIVERSITY OF CAMBRIDGE
Boies

imdea
instituto madrileño de estudios avanzados
Vilatela

UNIVERSITÀ DI PARMA
Carfagni

POLITECNICO MILANO 1863
Maestri

KIST
Kim

CREATING THE FUTURE

Informed by industry needs

Neutral ground for corporate partners

Academically grounded by Rice University

Independently steered by centralized governance

Mark Goulthorpe, MIT
House in 6 parts, WOJR

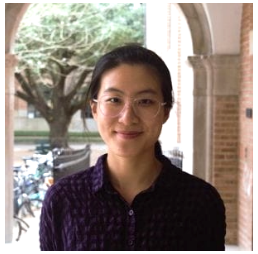
CURRENT GROUP

Steven Williams, CHBE
Tulane

Oliver Dewey, CHBE
CO School of Mines

Mitchell Trafford, CHBE
U Tulsa

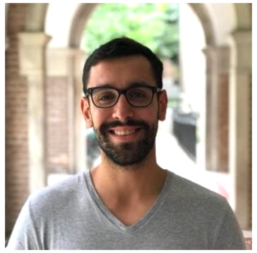
Muxiao Li, CHEM
U Maryland



Anavi Benavides, CHEM
TEC de Monterrey

Cedric Ginestra, CHBE
UT Austin

Ivan Siqueira, CHBE
PUC Rio



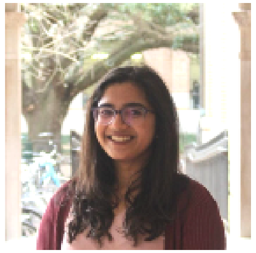
Michelle Duran, CHEM
U de Costa Rica

Alex Dantzler, CHBE
UT Austin

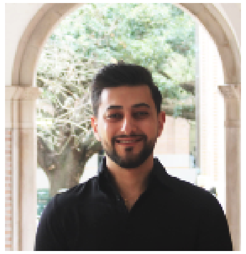
Arthur Sloan, CHBE
Auburn U

Lily Gong, CHBE
Auburn U

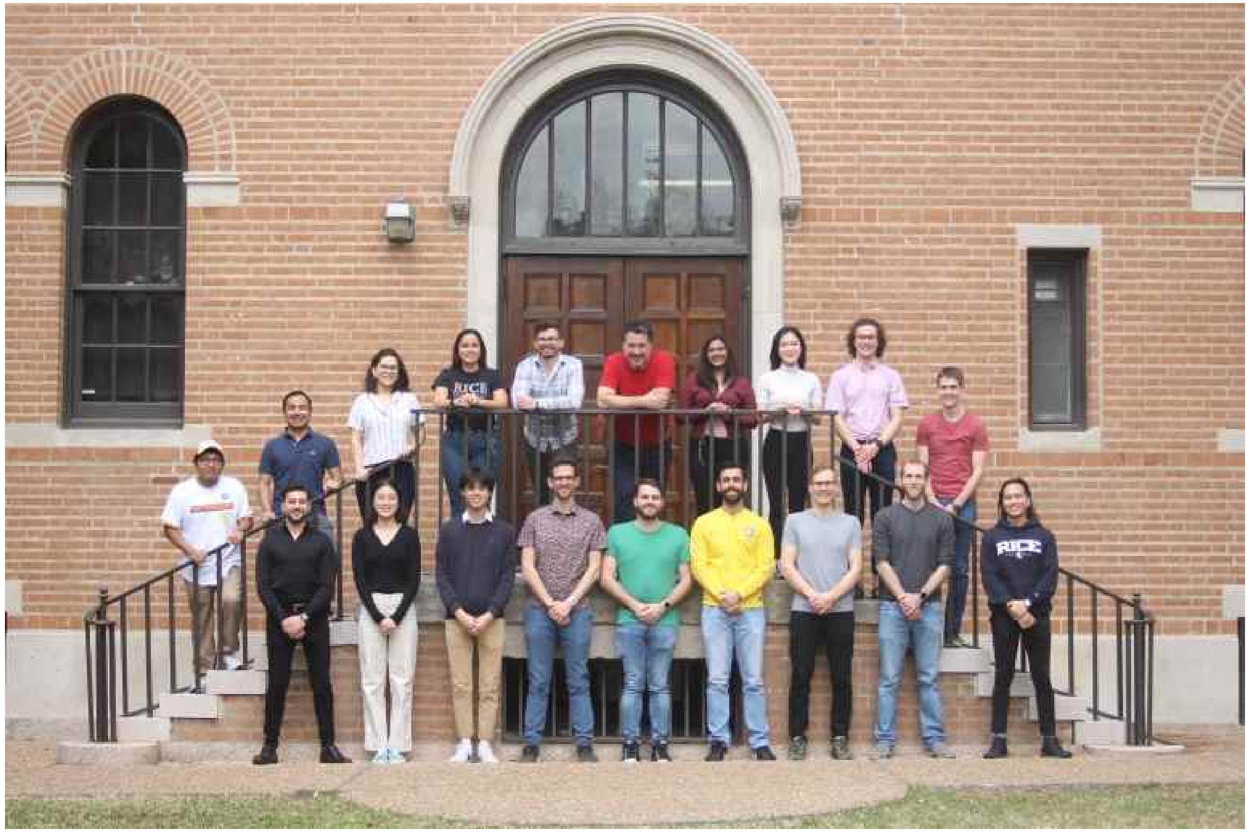
Jui Junnakar, CHBE
BITS Pilani



Joe Khoury, CHBE
Cleveland State U



Close collaboration with Dr. Glen Irvin



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