RESEARCH ON TAP

Developing Technologies for a Sustainable Future

Wednesday, December 7, 2022

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BOSTON UNIVERSITY

Boston University Office of Research

Agenda

- Welcome Remarks
- Presentations
  - Sean J. Elliott
  - James Chapman
  - Björn Reinhard
  - Xi Ling
  - Chuanhua Duan
  - Sean Lubner
  - Emily Ryan
  - Jörg Werner
  - Ayse K. Coskun
  - Srikanth Gopalan
  - Robert K. Kauffmann
  - Benjamin K. Sovacool
- Closing Remarks

Fixing Carbon and Breaking Nitrogen:
A Bioinorganic Chemist's Guide to Sustainability

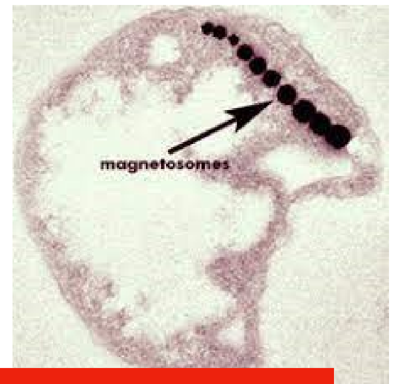
Sean J. Elliott

Professor
Chemistry, CAS
Bioinformatics and Materials Science & Engineering Programs, ENG
@prof_sje elliott@bu.edu sites.bu.edu/sje-lab

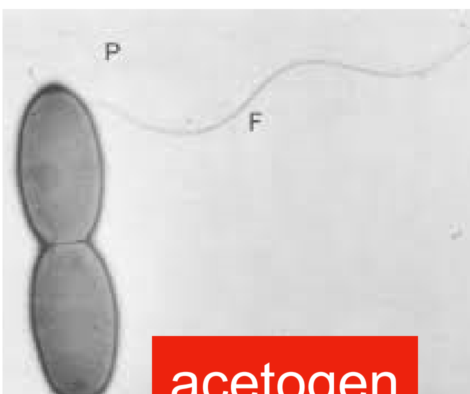
Fixing Carbon: Looking to Nature

microbial CO_2 fixers

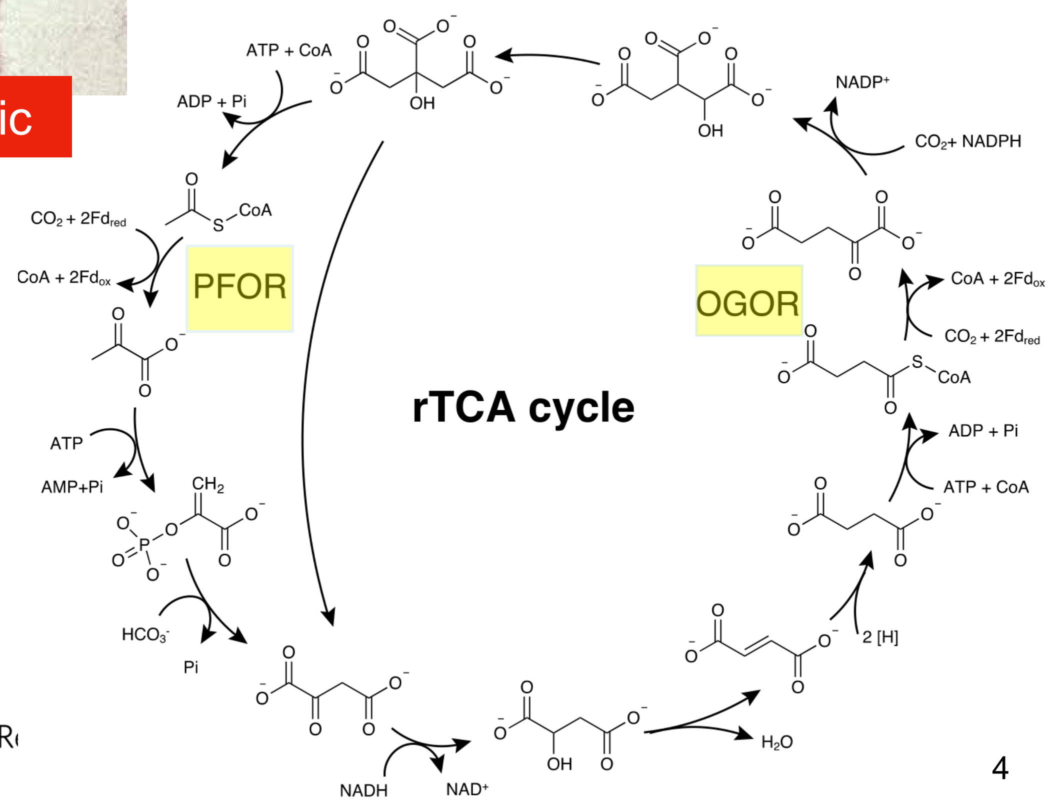
methanogen



magnetotactic



acetogen



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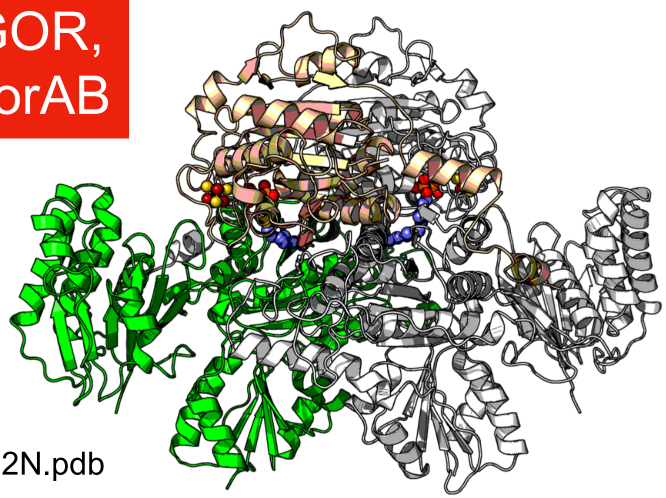
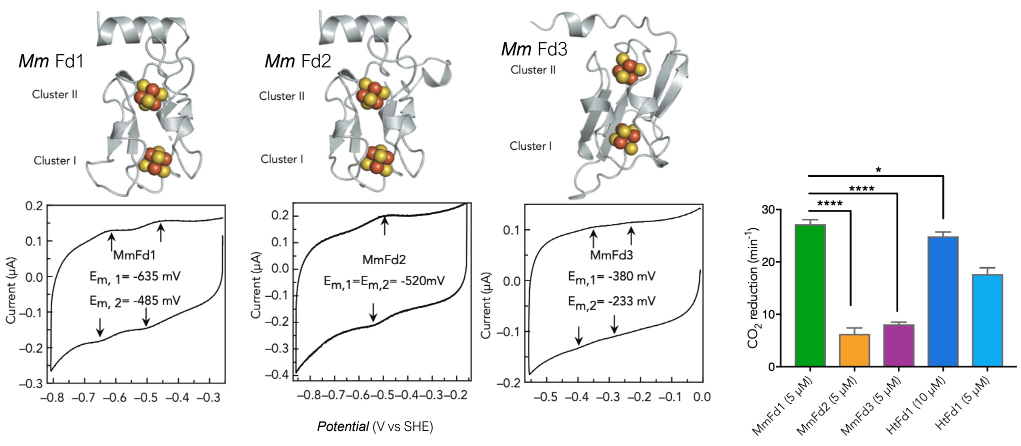
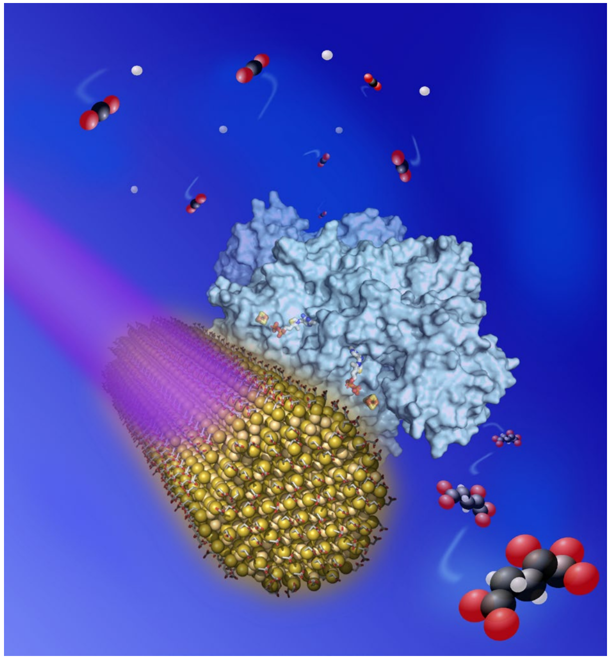
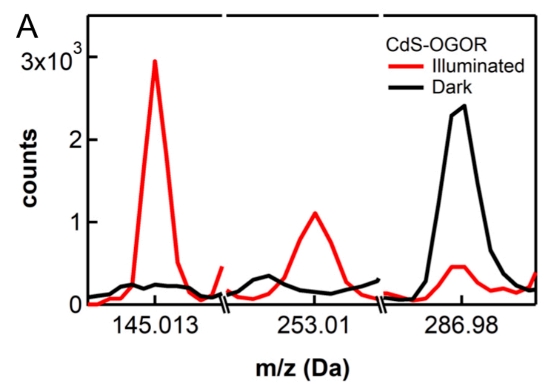
Enzymes that fix CO_2…

An OGOR, Mm KorAB









… & do so with light

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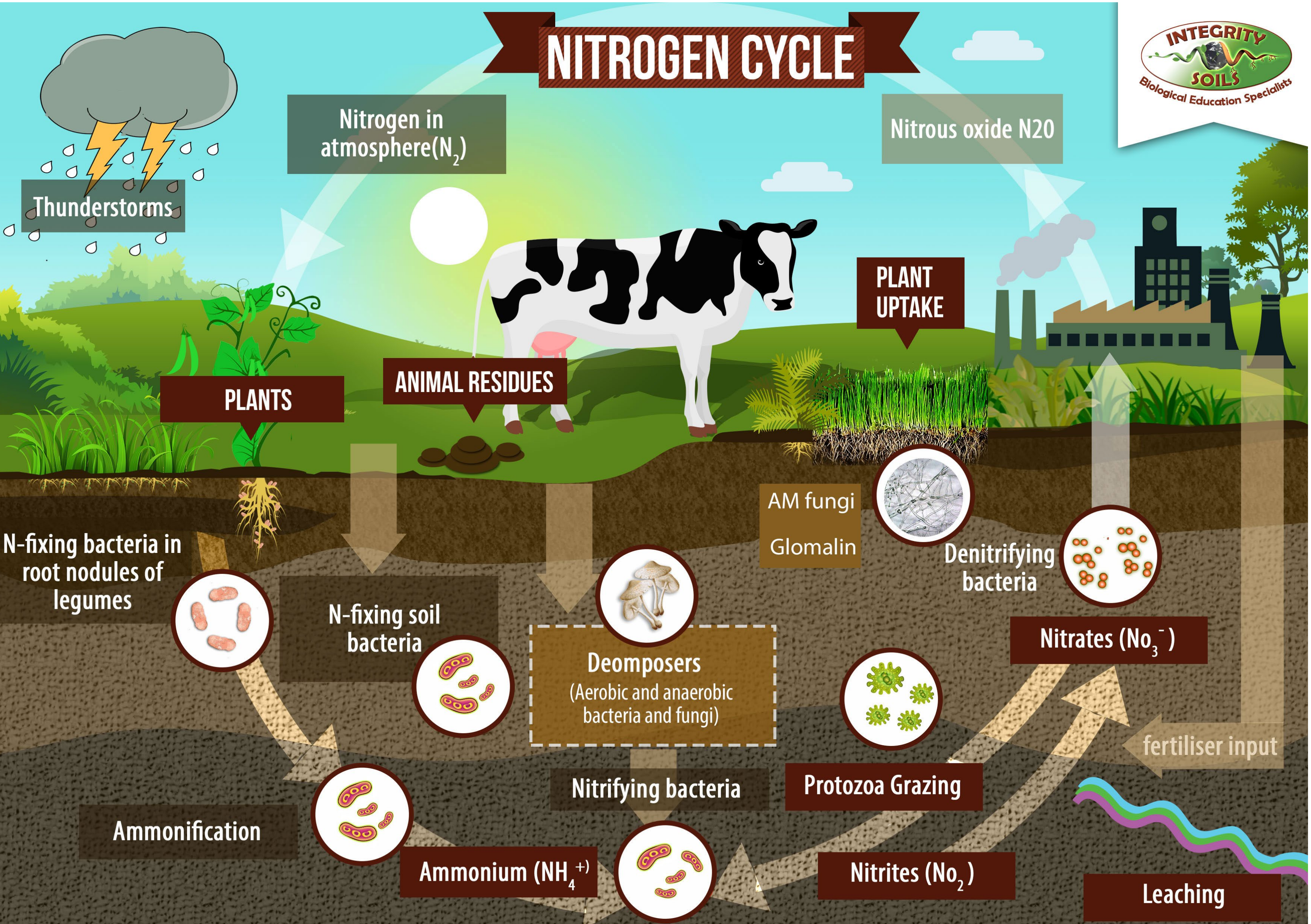
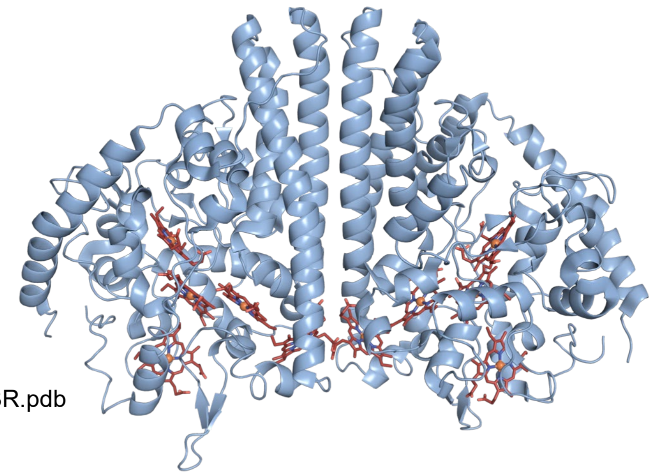
Chen et al., Joule (2019); Hamby et al., *PNAS* (2020)

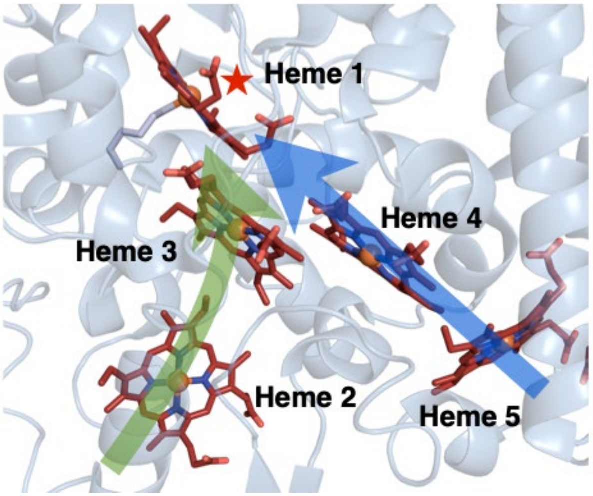
Breaking Nitrogen

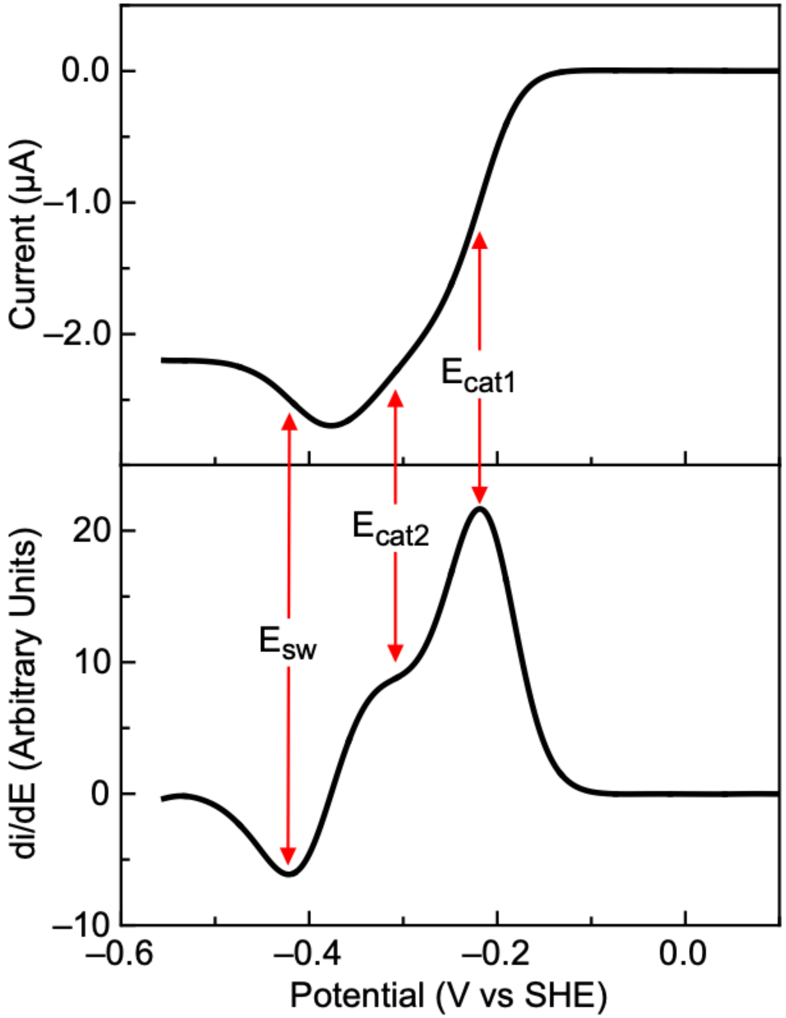


Enzymes that make ammonia…



So ccNiR 3UBR.pdb





… and mop up nitrites

Judd et al., Biochemistry (2015); unpublished work with Geobacter enzymes

Towards a Better Future for Humankind: Intelligent Design of Novel Materials for Catalyst Design

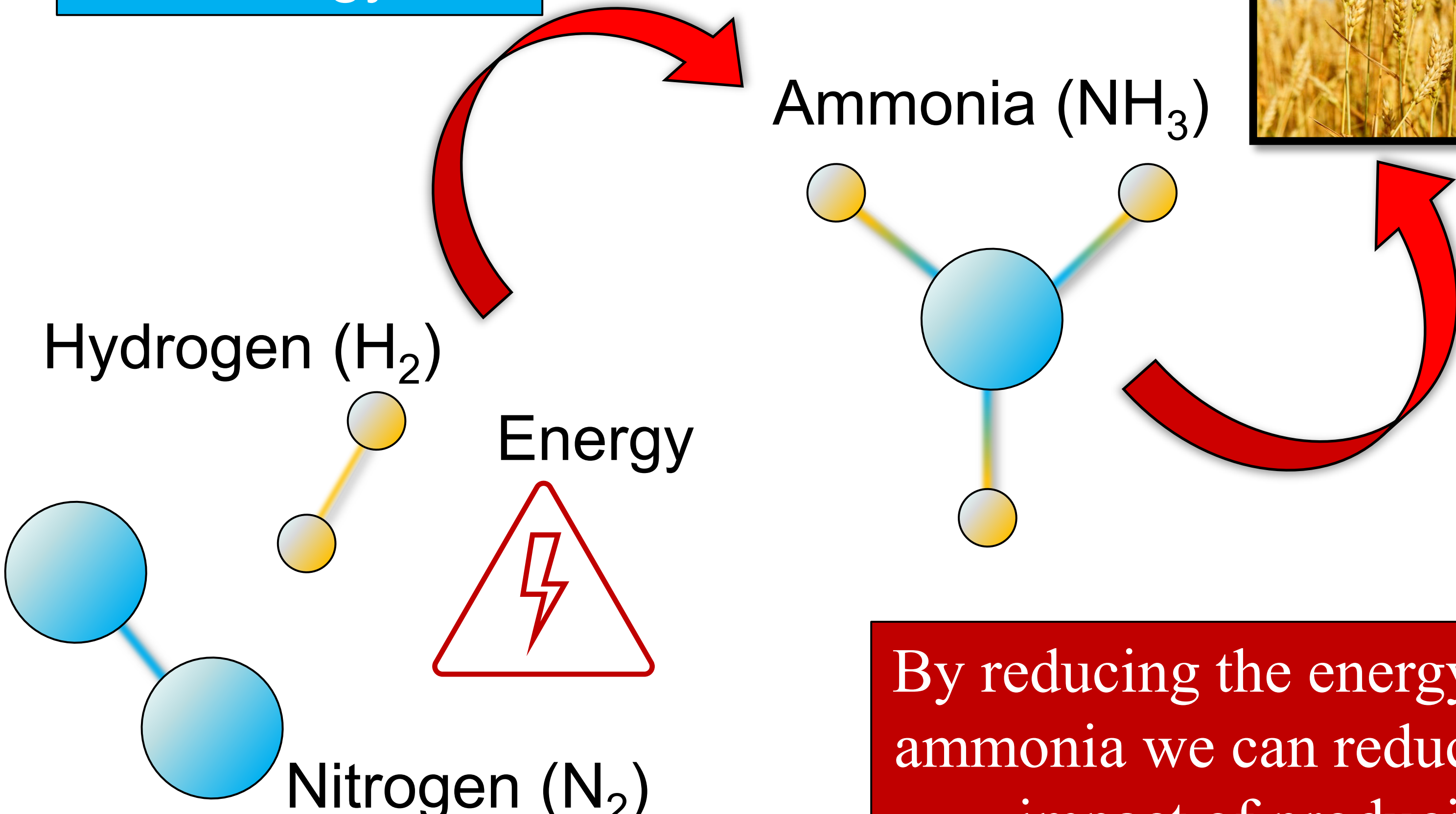
James Chapman

Assistant Professor
Department of Mechanical Engineering
Division of Materials Science and Engineering
ENG

Catalysts: what are they and why you should care?

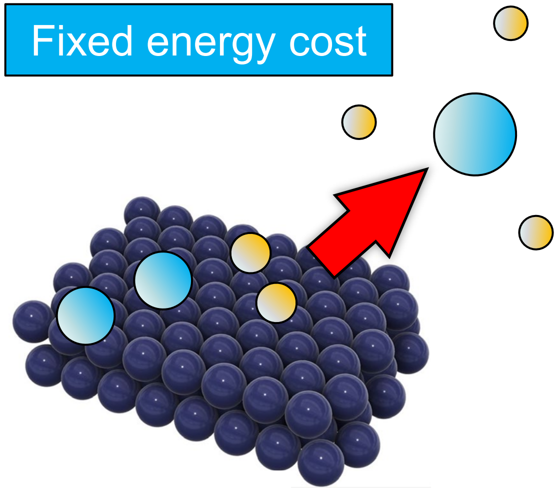
Food

Catalyst: lowers energy

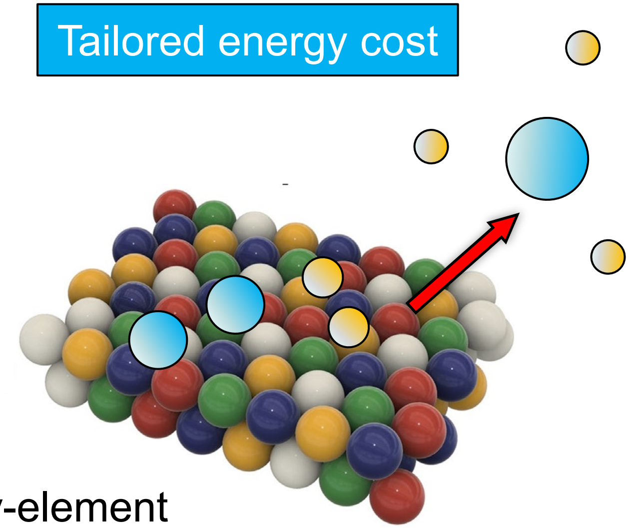


By reducing the energy cost to form ammonia we can reduce the climate impact of producing food.

How are we designing the next generation of catalysts?



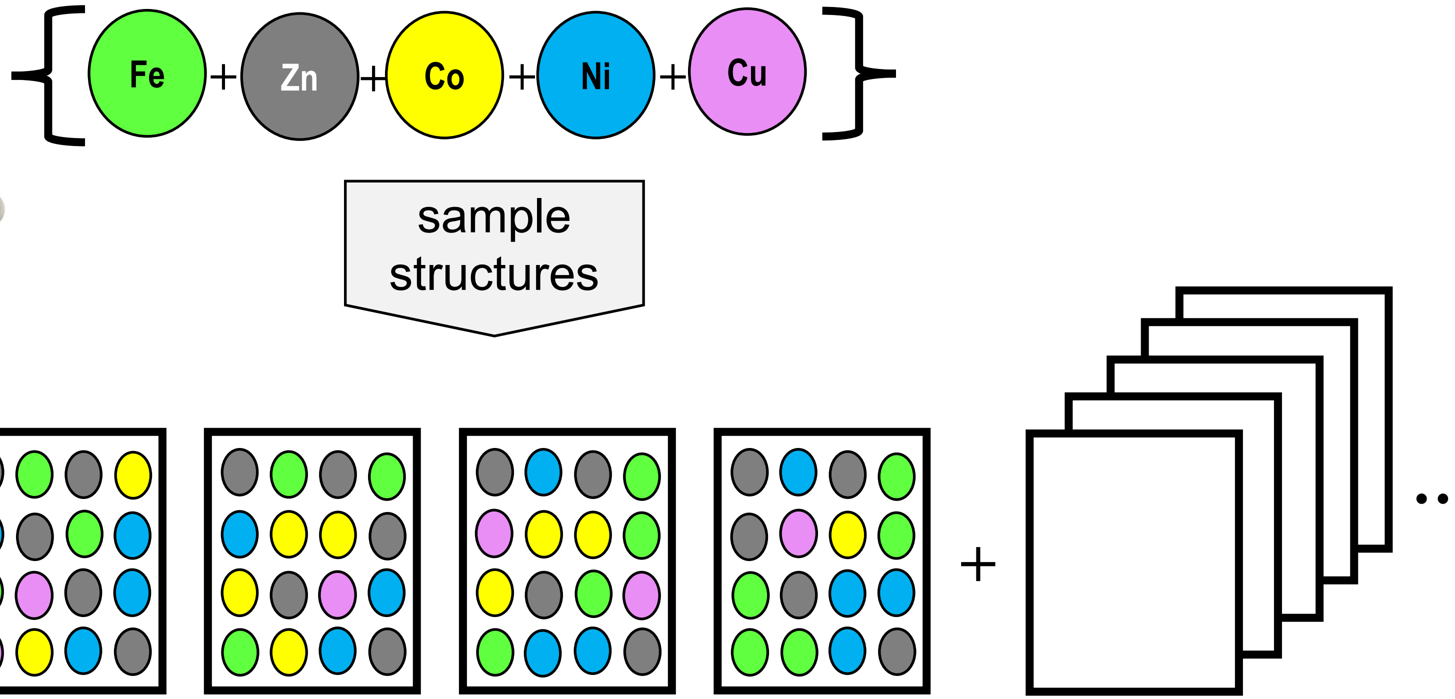
Single element catalyst



Many-element (HEA) catalyst

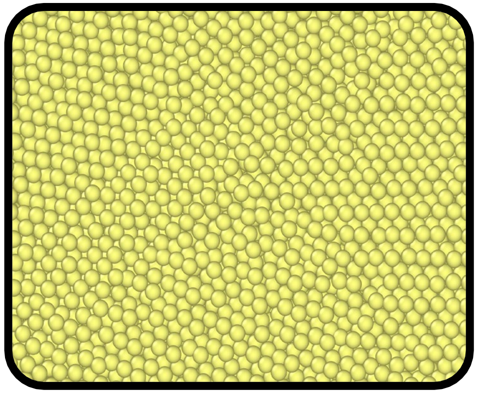
Moving towards HEA catalysts gives us the ability to greatly reduce the energy required to produce ammonia.

So why haven't we figured it out yet?

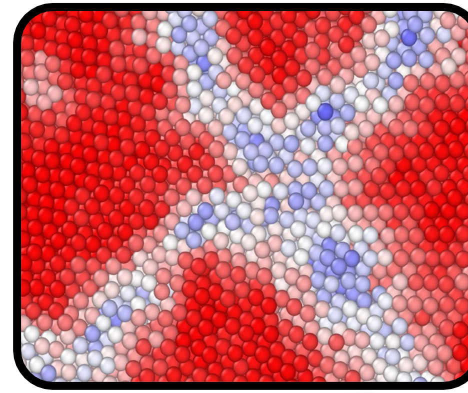


Finding an optimal HEA catalyst becomes
a materials screening problem.

How do we embed our intuition/knowledge into the design process?



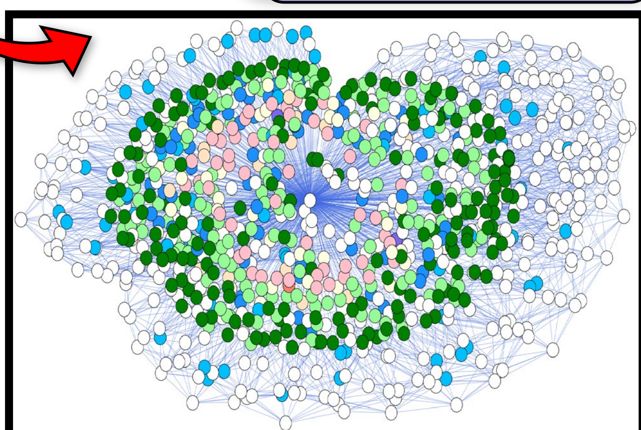
Machine learning can help us quantify complex differences between groups of atoms.

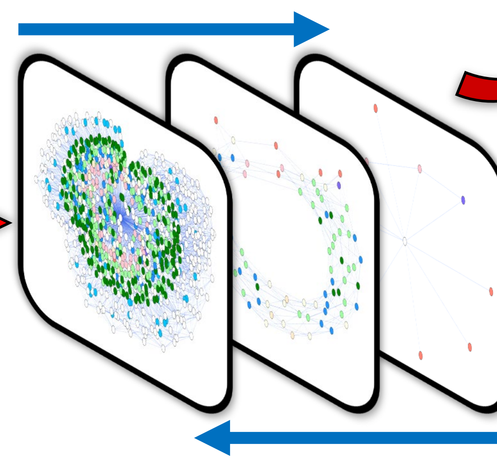


Atoms

Quantifying atoms

Representation of atoms





Machine learning

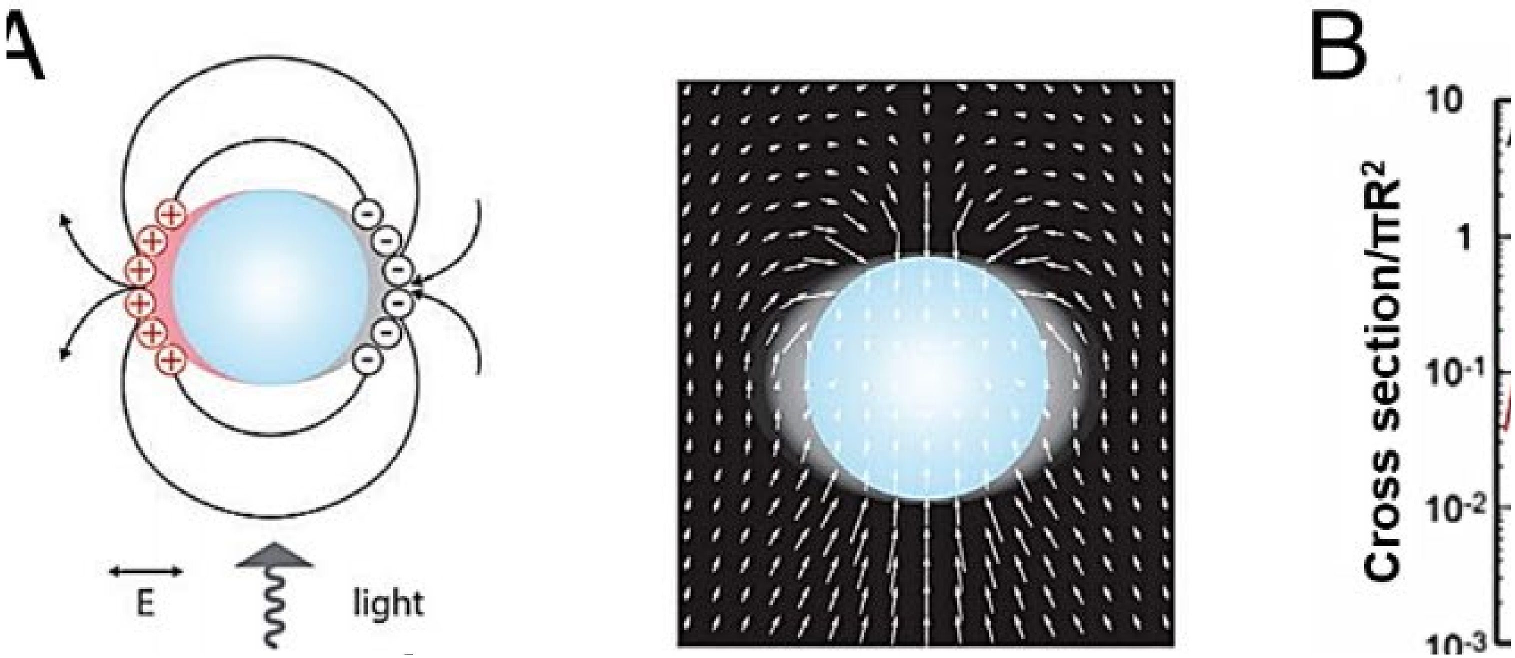
Chapman et. al. *under review (Nat. Comm.)*

Plasmonic Nanoreactors

Björn M. Reinhard

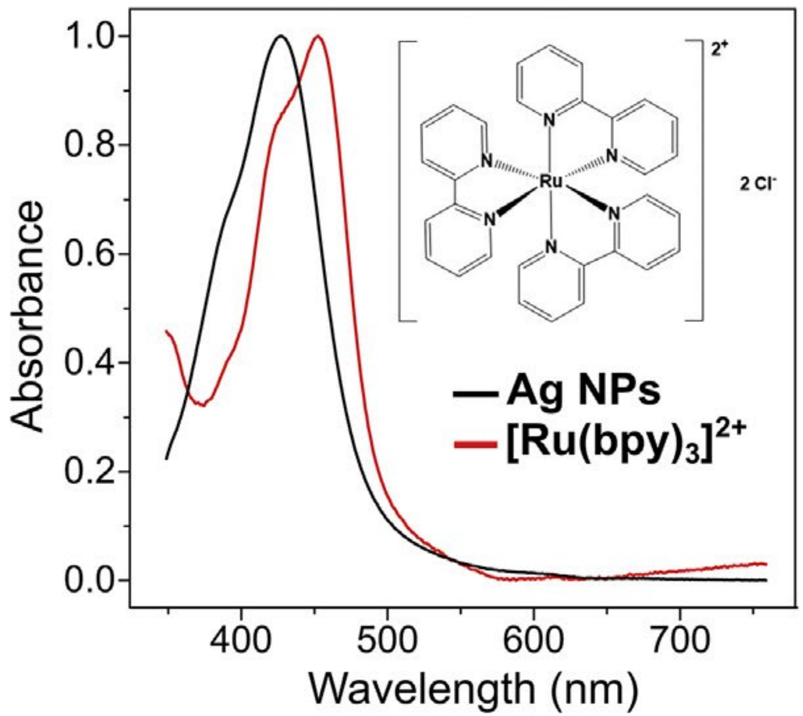
Professor
Chemistry, CAS

Plasmon-Enhanced Photoredox Catalysis in Hybrid Materials

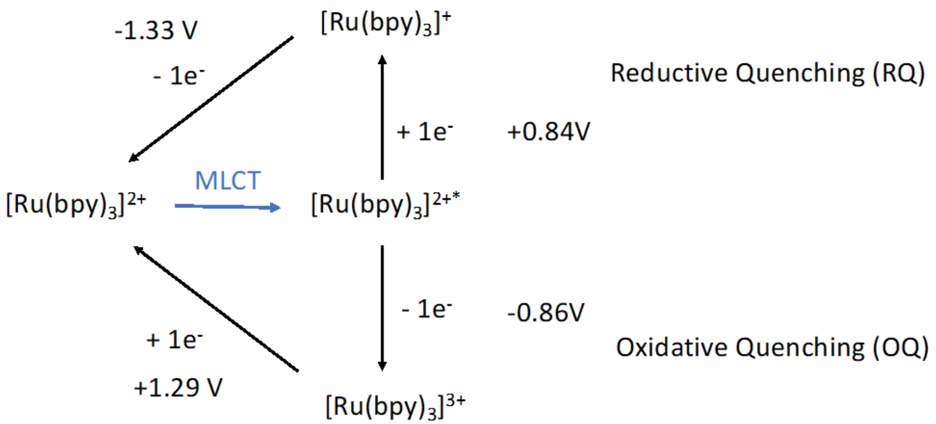


Hong and Reinhard, J. Opt. 21, 113001 (2019).

Plasmon-Enhanced Photoredox Catalysis

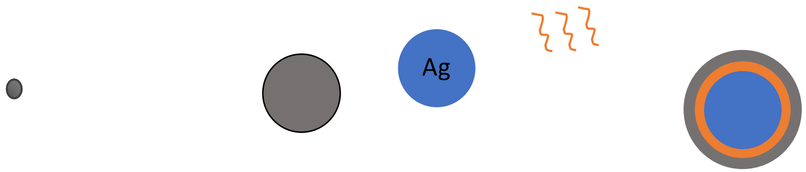


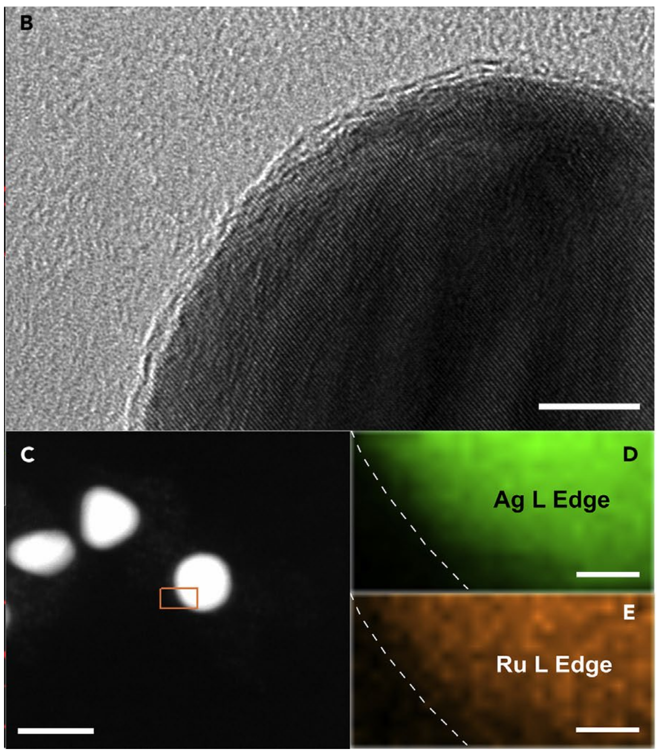
X. An et al., Chem. 5, 2228 (2019).

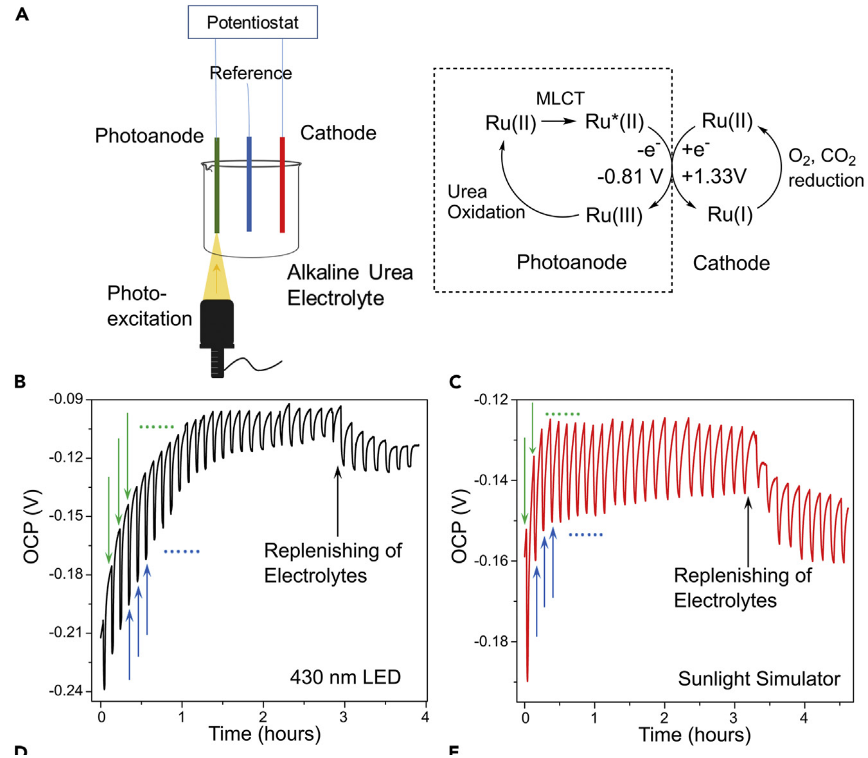


Narayanam and Stephenson, Chem. Soc. Rev. 40, 5322 (2011)
Corrigan et al., Chem. Soc. Rev. 45, 6165 (2016)

Light Driven Direct Urea Fuel Cell

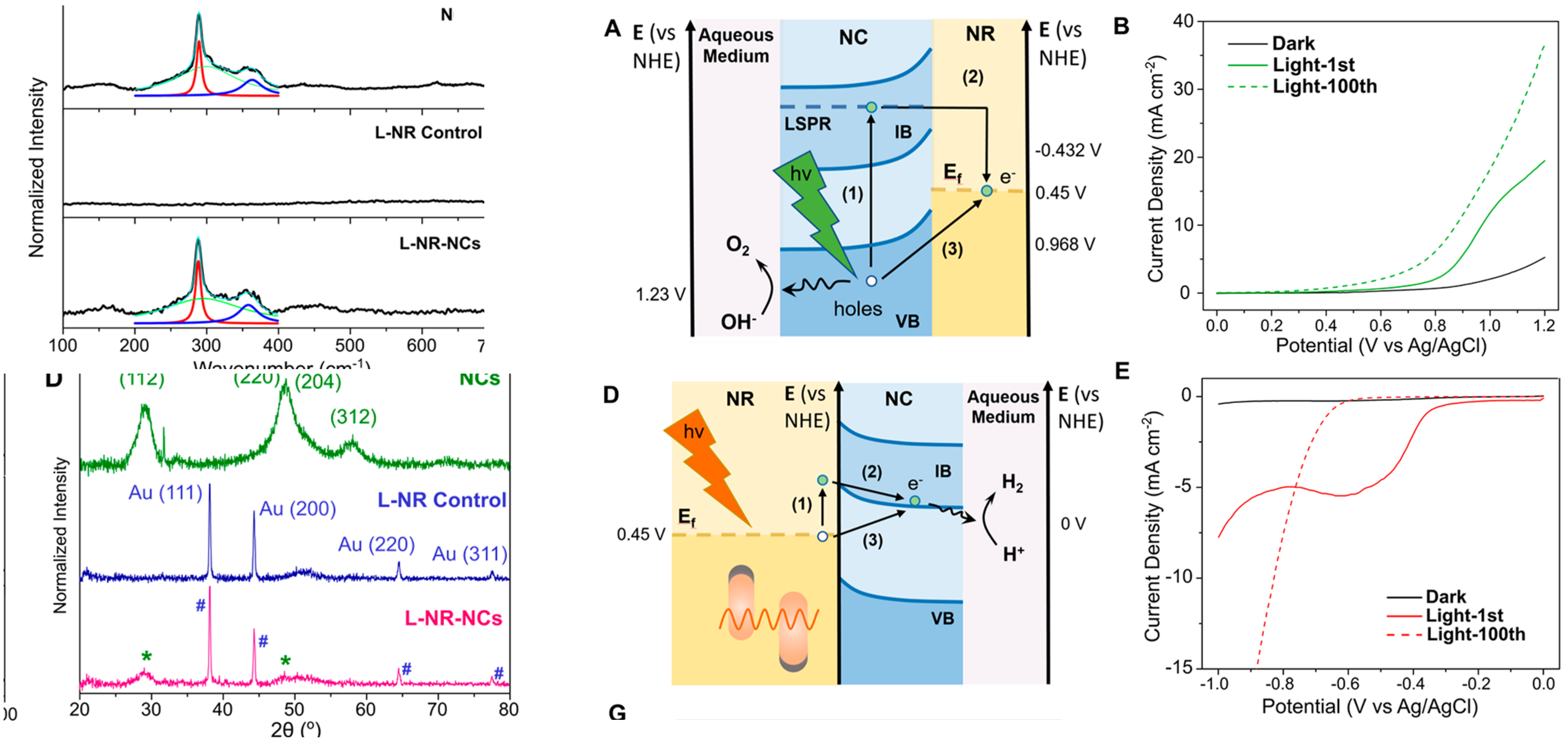






X. An et al., Chem. 5, 2228 (2019).

Bifunctional Plasmonic Photocatalysi in Au/Chalcopyrite Nanohybrids



X. An et al., ACS Nano 16, 6813 (2022).

Atomically Thin Materials for Electrochromic Devices

Coloring with Less Energy

Xi Ling

Assistant Professor
Chemistry, CAS

Display power used in Times Square alone could power…

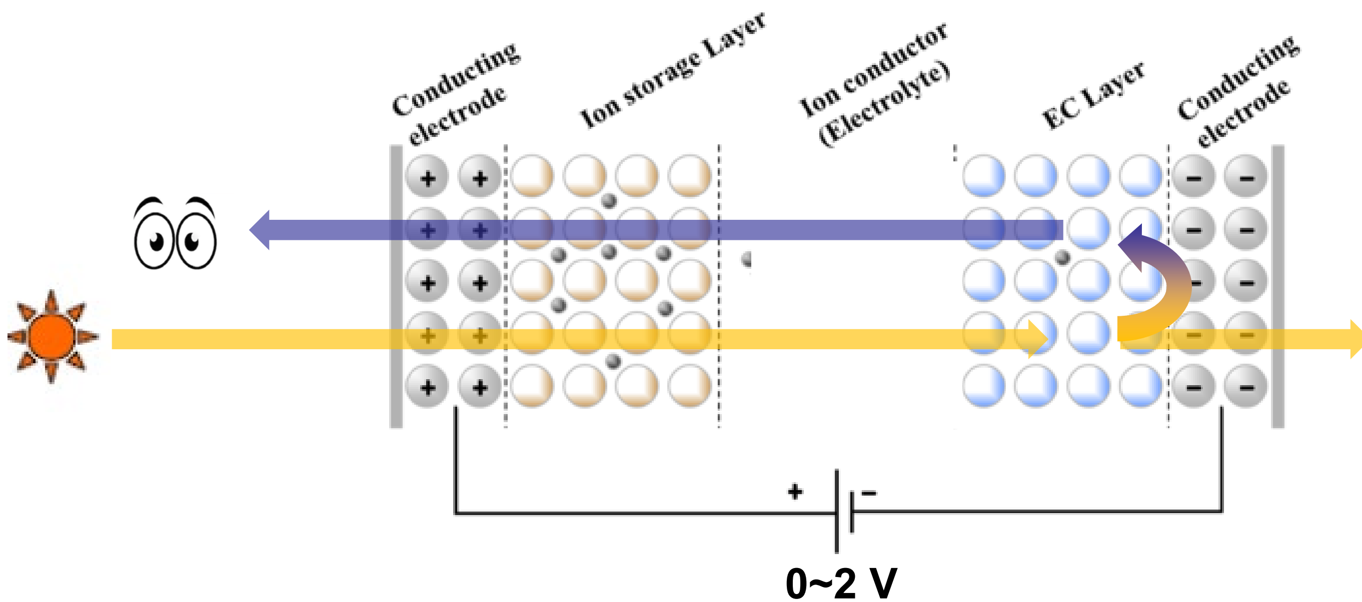
Times Square, New York

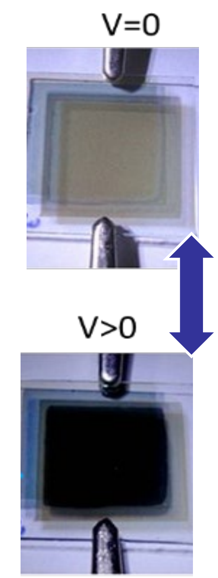
161 MW
per day

$135 K
per day

- 161,000 average US homes
- Light 1.6 million 100-watt light bulbs
- The entire country of Turks and Caicos

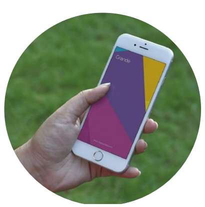
Electrochromic (EC) materials change color under small voltage





Digital signage

Glass building



Phone display

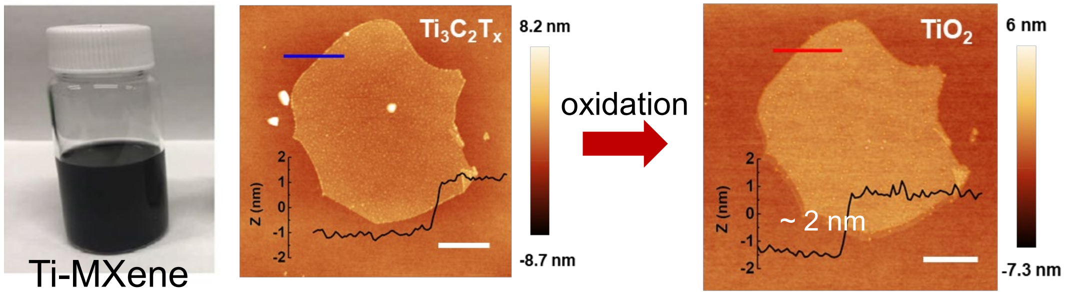
Flight window

Automotive

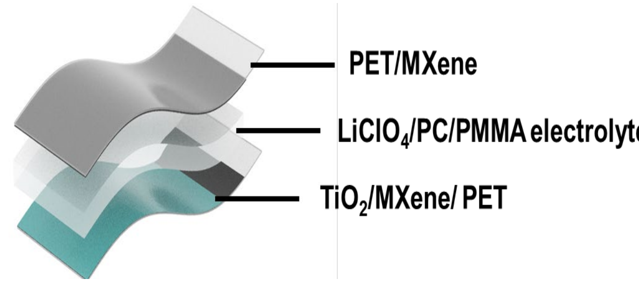
- Save energy
- Improve readability & comfort
- Across diverse industries

2D networked structure helps improve the EC performance

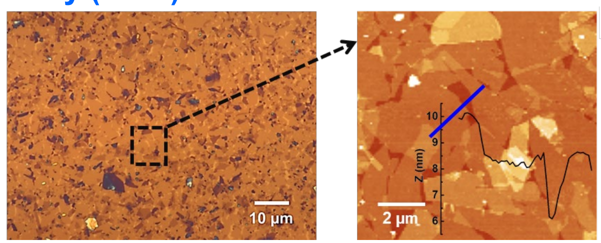
Preparation of highly conductive Ti-Mxene and EC 2D TiO_2

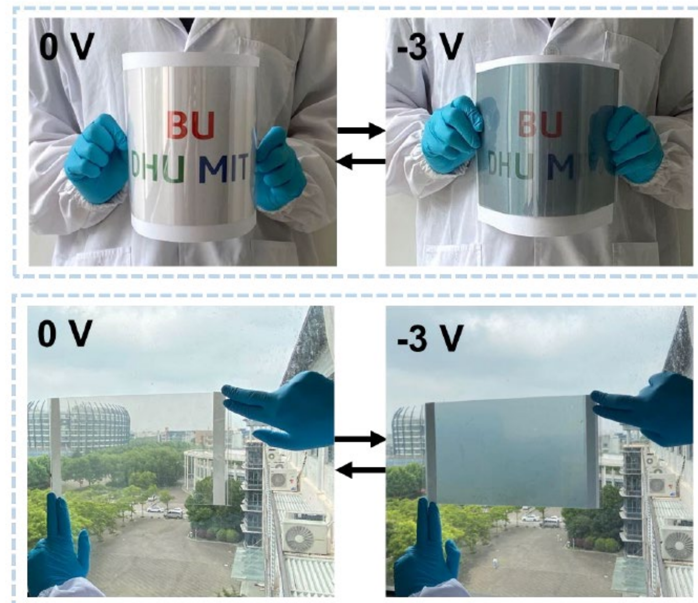


EC device and performance



liquid-liquid interface assembly (LLIA)





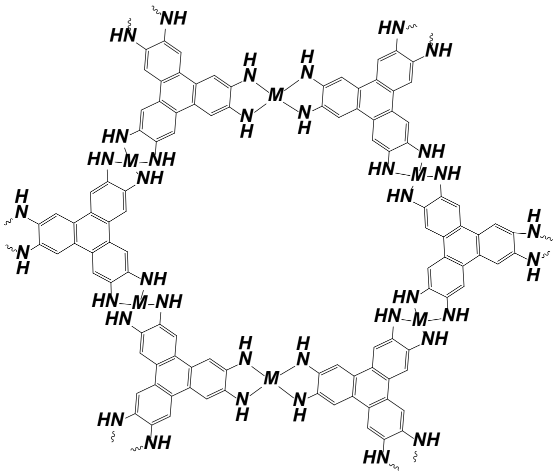
Our device:

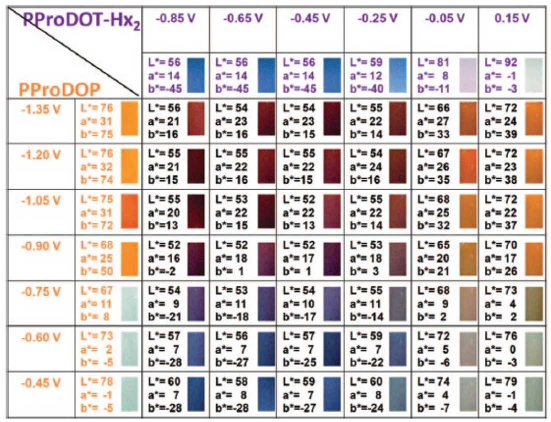
- ✓ Higher optical modulation range
- ✓ Highest coloration efficiency
- ✓ The most fast temporal response
- ✓ Excellent stability

R. Li, X. Ling et al., *Nature Comm.*, 2021, 12 (1), 1-11

Ongoing in Ling group: 2D Metal-Organic-Framework (MOF) to show more color states

2D MOFs

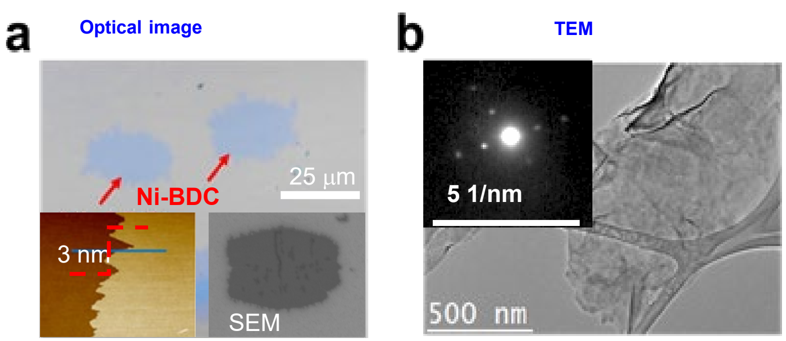


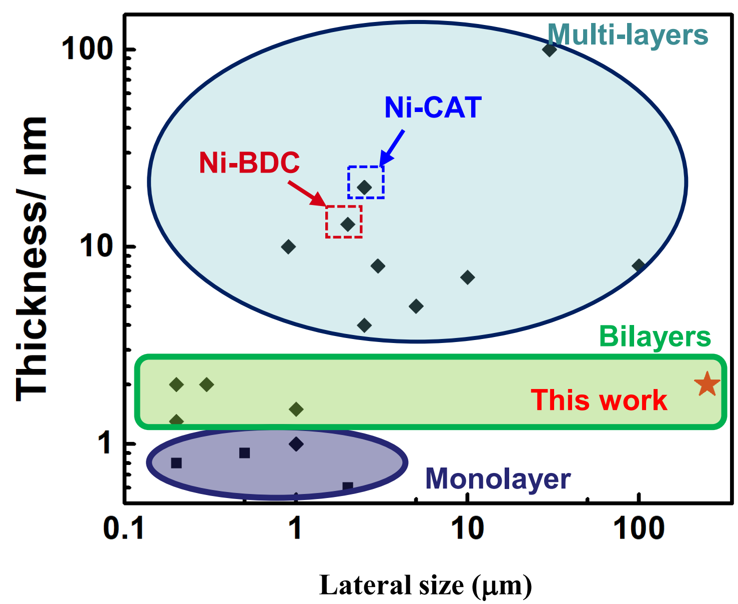


PProDOP \ PProDOT-Hx_2		-0.85 V	-0.65 V	-0.45 V	-0.25 V	-0.05 V	0.15 V
		L*= 56 a*= 14 b*=-45	L*= 56 a*= 14 b*=-45	L*= 56 a*= 14 b*=-45	L*= 59 a*= 12 b*=-40	L*= 81 a*= 8 b*=-11	L*= 92 a*= -1 b*= -3
-1.35 V	L*= 76 a*= 31 b*= 75	L*= 56 a*= 21 b*=16	L*= 54 a*= 23 b*= 16	L*= 54 a*= 23 b*= 15	L*= 55 a*= 22 b*= 14	L*= 66 a*= 27 b*= 33	L*= 72 a*= 24 b*= 39
-1.20 V	L*= 76 a*= 32 b*= 74	L*= 55 a*= 21 b*=15	L*= 55 a*= 22 b*= 16	L*= 55 a*= 22 b*=15	L*= 54 a*= 24 b*=16	L*= 67 a*= 26 b*= 35	L*= 72 a*= 23 b*= 38
-1.05 V	L*= 75 a*= 31 b*= 72	L*= 55 a*= 20 b*=13	L*= 53 a*= 22 b*= 15	L*= 52 a*= 22 b*= 13	L*= 55 a*= 22 b*= 14	L*= 68 a*= 25 b*= 32	L*= 72 a*= 22 b*= 37
-0.90 V	L*= 68 a*= 25 b*= 50	L*= 52 a*= 16 b*=-2	L*= 52 a*= 18 b*= 1	L*= 52 a*= 17 b*= 1	L*= 53 a*= 18 b*= 3	L*= 65 a*= 20 b*= 21	L*= 70 a*= 17 b*= 26
-0.75 V	L*= 67 a*= 11 b*= 8	L*= 54 a*= 9 b*=-21	L*= 53 a*= 11 b*=-18	L*= 54 a*= 10 b*=-17	L*= 55 a*= 11 b*=-14	L*= 68 a*= 9 b*= 2	L*= 73 a*= 4 b*= 2
-0.60 V	L*= 73 a*= 2 b*= -5	L*= 57 a*= 7 b*=-28	L*= 56 a*= 7 b*=-27	L*= 57 a*= 7 b*=-25	L*= 59 a*= 7 b*=-22	L*= 72 a*= 5 b*= -6	L*= 76 a*= 0 b*= -3
-0.45 V	L*= 78 a*= -1 b*= -5	L*= 60 a*= 7 b*=-28	L*= 58 a*= 8 b*=-28	L*= 59 a*= 7 b*=-27	L*= 60 a*= 8 b*=-24	L*= 74 a*= 4 b*= -7	L*= 79 a*= -1 b*= -4

- ✓ Multicolor
- ✓ Flexible
- ✓ Stable
- ✓ Color memory

Our patented largest 2D MOF domains





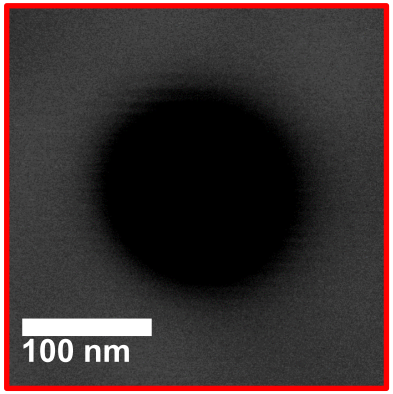
Exploring & Regulating Mass Transport Across Nanopores for Sustainable Electronics and Carbon Footprint

Chuanhua Duan

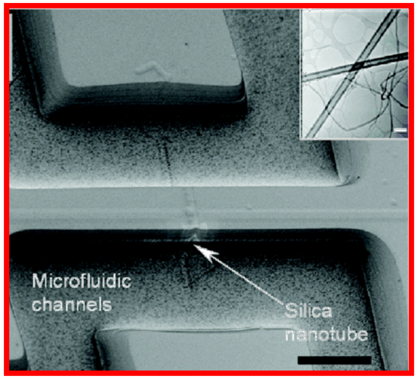
Associate Professor
Mechanical Engineering, ENG

The Nanoscale Energy and Fluids Transport (NEFT)Laboratory

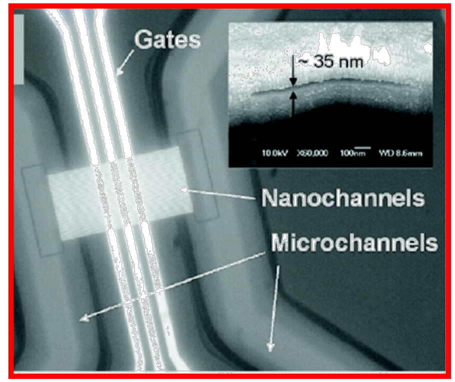
Study and Application of Energy and Fluids Transport in/around Nanoscale Objects



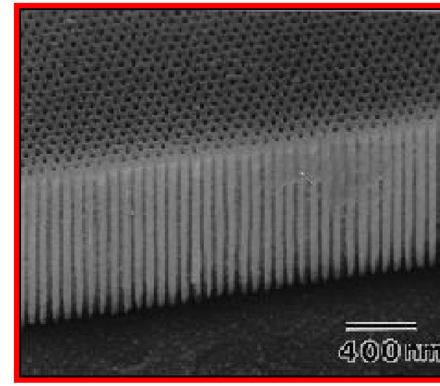
Nanopore



Nanotube/Nanowire



Nanochannel

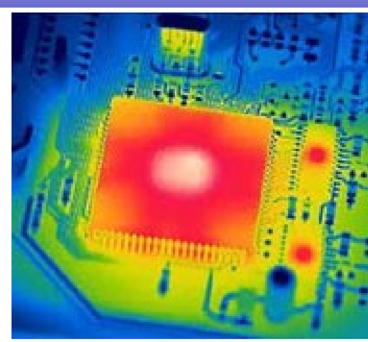


Mesoporous Membrane

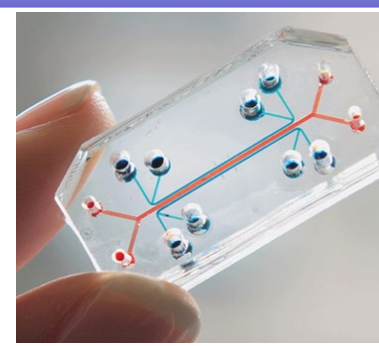
Applications

Water Desalination

Energy Conversion/Storage



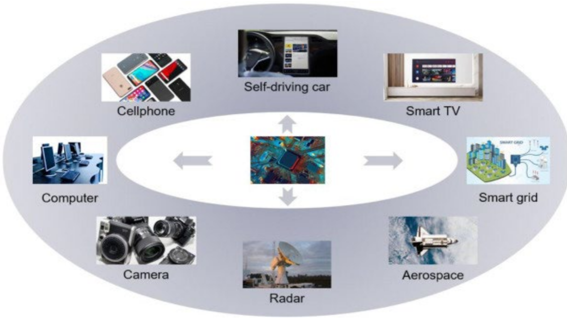
Electronics Cooling



Point Care

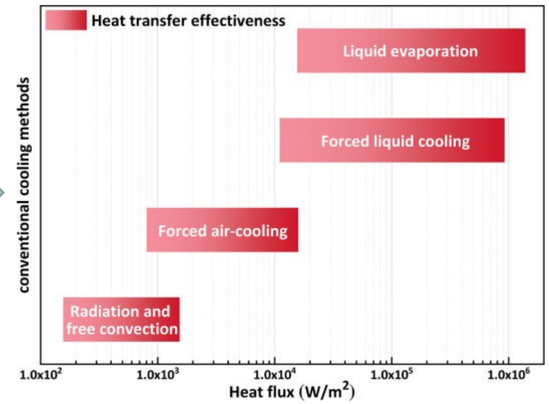
Building Energy

Exploring Kinetically-Limited Evaporation from Nanoporous Membranes for Sustainable Electronics



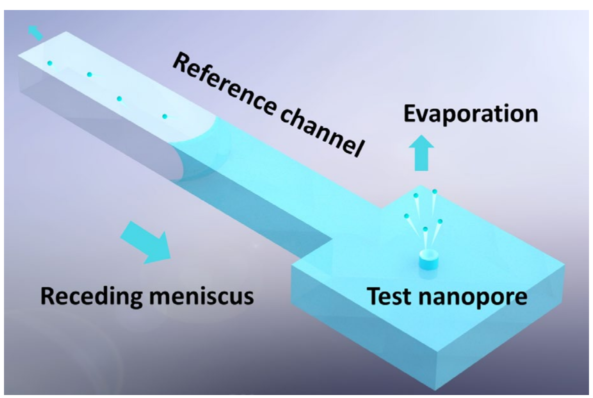
High Density,
Smaller, Thinner and Lighter

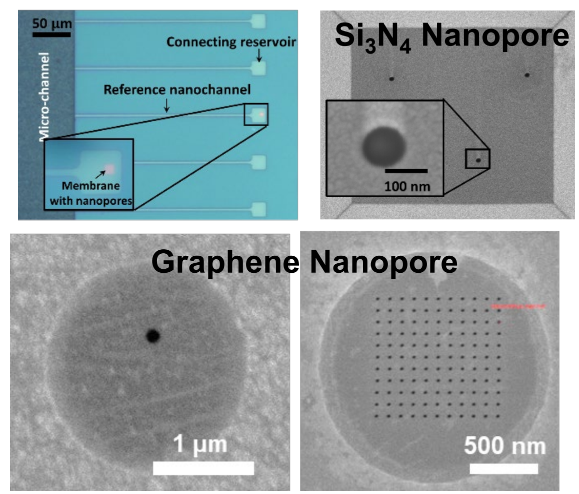
heat flux up to 5-10 MW/m^2



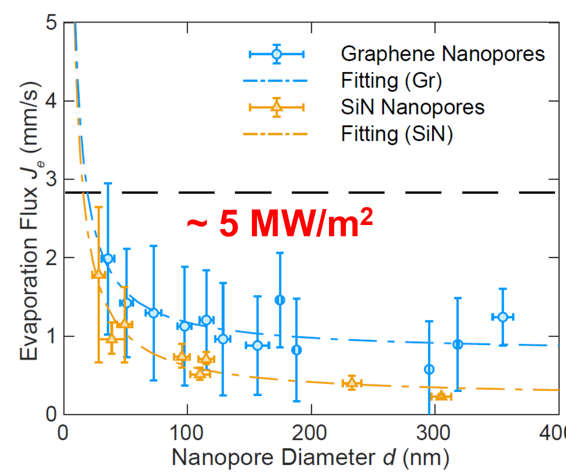
Z. Zhang *et al.*, *e-Prime*, (2021)

What is the ultimate evaporation performance determined by the evaporation kinetics?





Kinetic limits @ 20℃



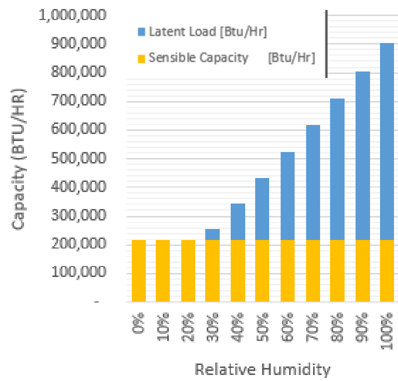
Y. Li et al., Nano Lett. (2017) Y. Li *et al.*, *ACS Nano. (2019)* S, Xiao et al., *Cell Rep. Phys. Sci.*, (2022)

Regulating Mass Transport through Nanopores for Sustainable Carbon Footprint

World needs AC

https://www.nytimes.com/

Latent cooling loading

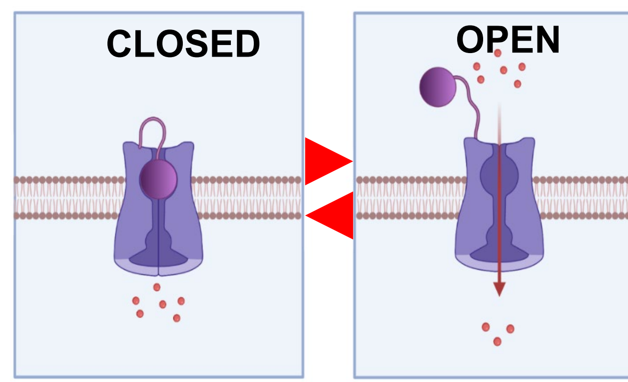


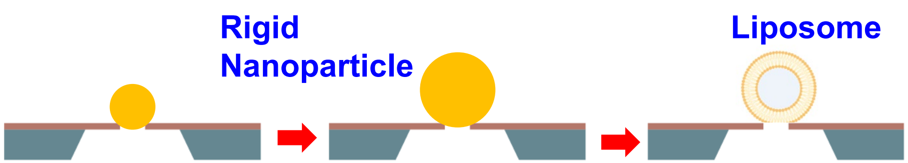
https://www.superradiatorcoils.com

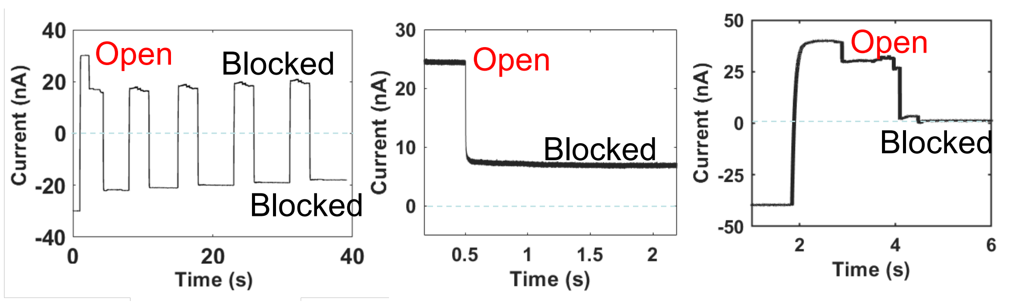
Energy-efficient, active/passive humidity control

Vapor Diode
Vapor Transistor

Stimuli-responsive mass transport regulation in cell membrane







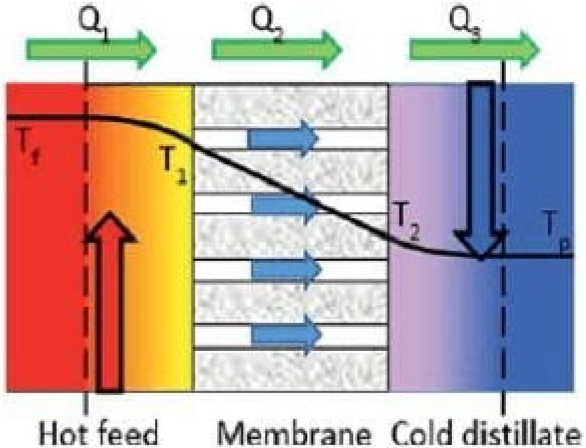
R. Yazbeck, et al., *Nanoscale*, (2019)

Y. Xu, et al., *JCP (2021)*

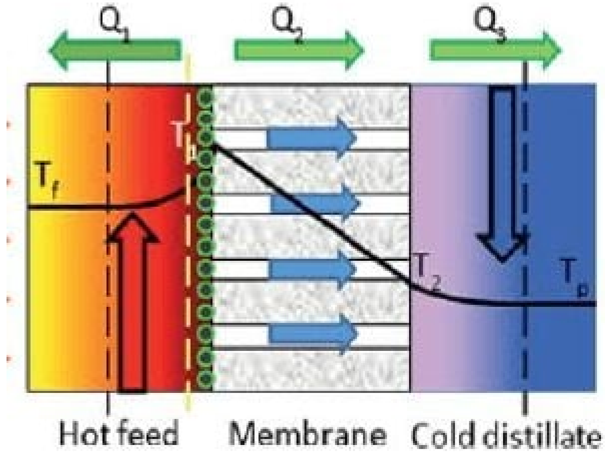
R. Yazbeck et al., *PNAS.*, (2022)

Novel Nanoporous Membranes for Surface Heating Membrane Distillation

Classical Membrane Distillation

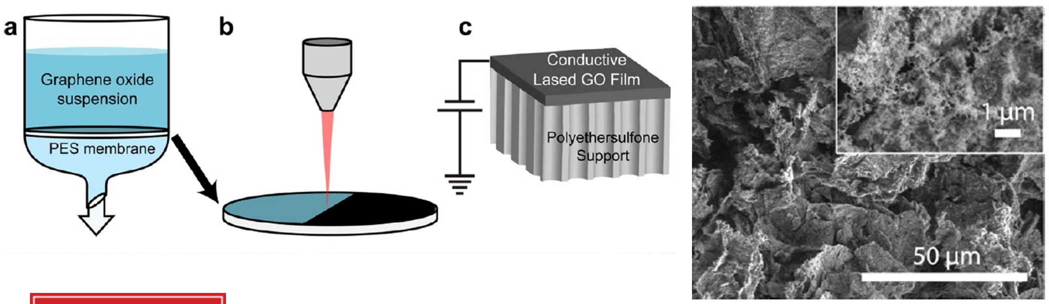


Surface Heating Membrane Distillation



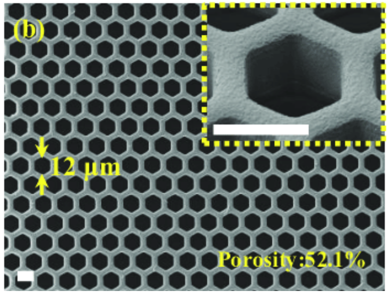
https://qilinli.rice.edu/research/

Scalable laser-reduced conductive and permeable graphene oxide membrane



A. Straub et al., *Nano Lett.*, (2021)

Ordered Parylene-C membrane with surface heating layer



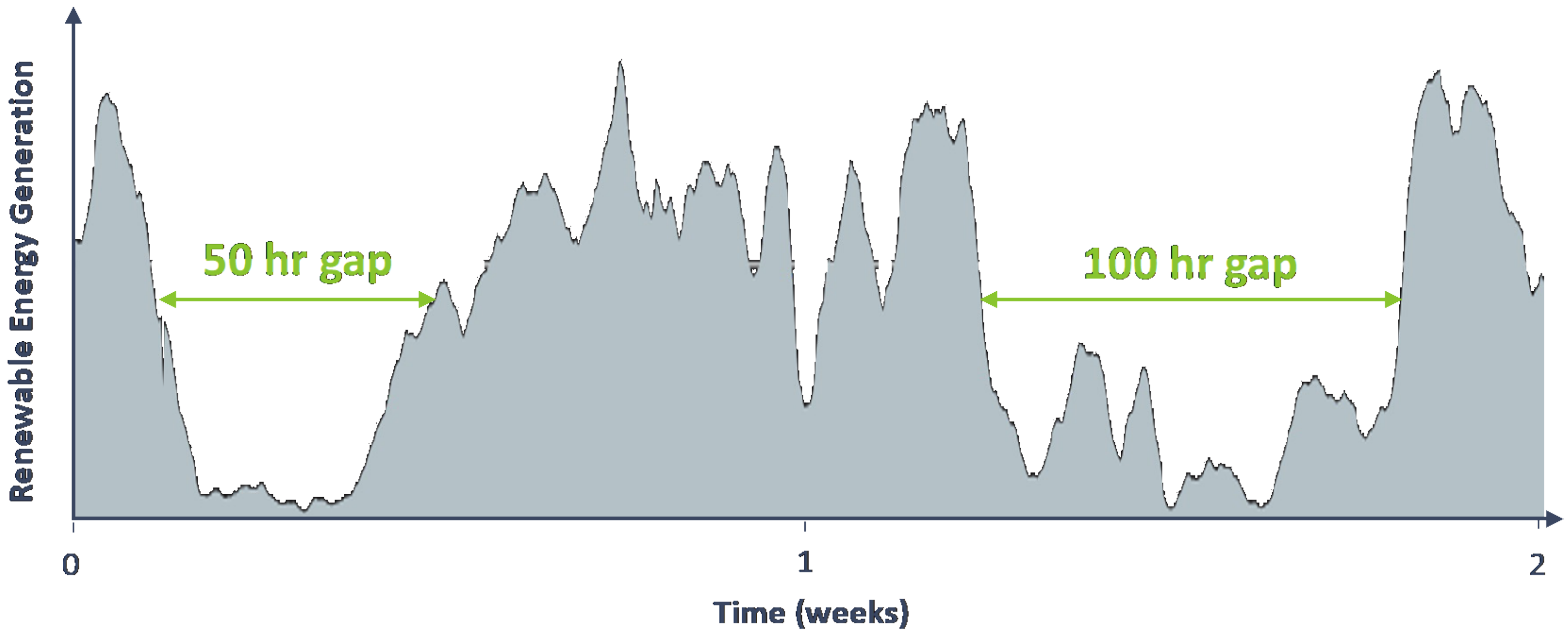
Y. Liu *et al.*, *MicroTAS*, (2015)

Reducing CO_2 Emissions Below Zero

Sean Lubner

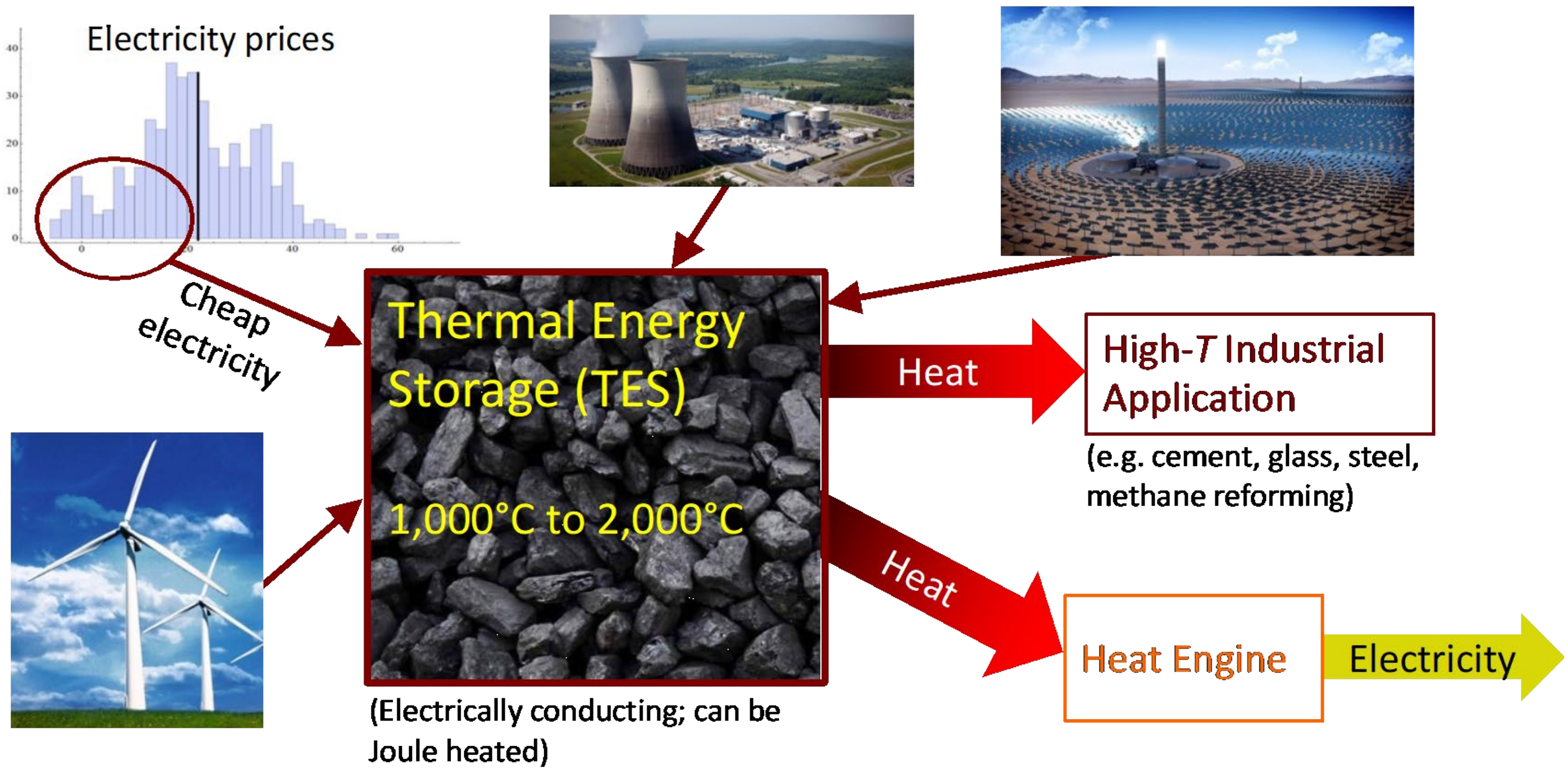
Assistant Professor
Mechanical Engineering
Materials Science & Engineering
ENG

Renewables supply & demand timing is mismatched, so we need energy storage



Plot courtesy of Antora Inc.

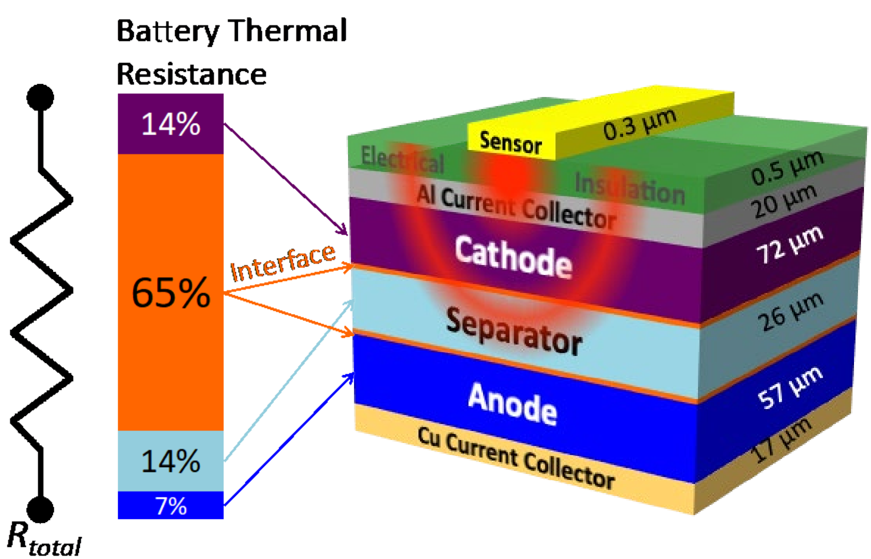
High-T thermal is promising for large scale storage



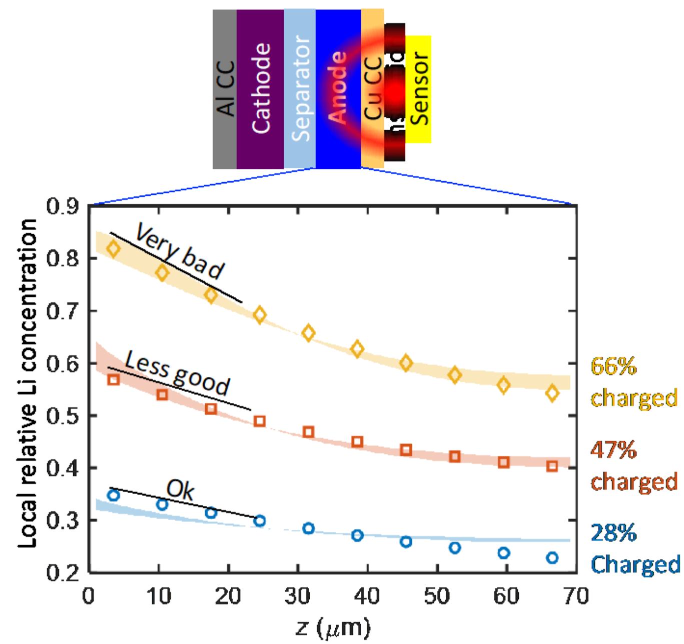
Cheap (LCOS < \$0.03/kWh$_{th}$), scalable (~1 MWh$_{th}$/m^3), safe, and can deploy anywhere.

Non-invasive Thermal Wave Sensors: real time subsurface property mapping (batteries, fuel cells, harsh environments)

Identified heat gets trapped at interfaces between battery layers.



Spatially mapped local Lithium distribution in live battery anode (microns resolution).

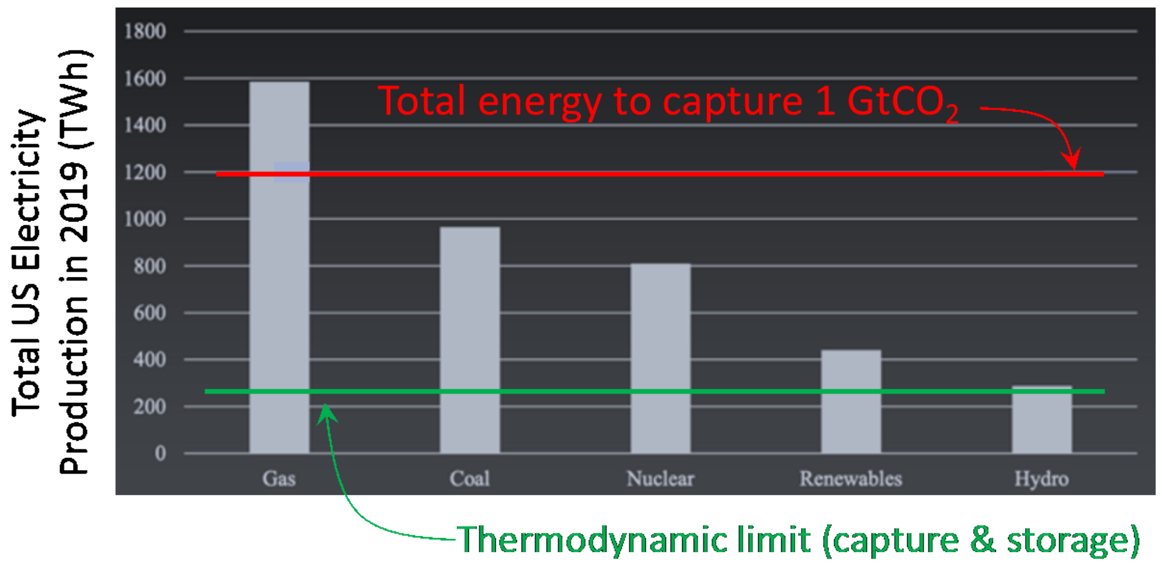


Removing CO_2 from the atmosphere

Humans emit 42 $GtCO_2$/yr.

We need to remove up to 10 $GtCO_2$/yr for decades to avoid catastrophe (even given zero emissions).

Direct Air Capture (DAC) of CO_2



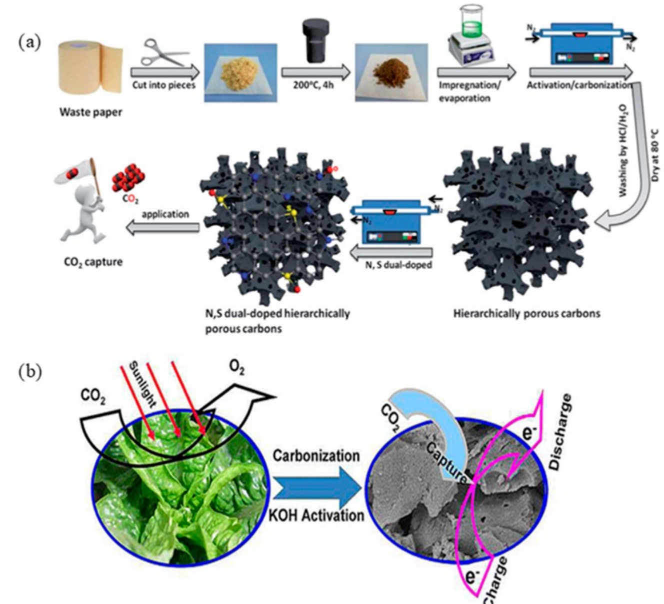
Interfacial Phenomena in Energy Technologies

Emily Ryan

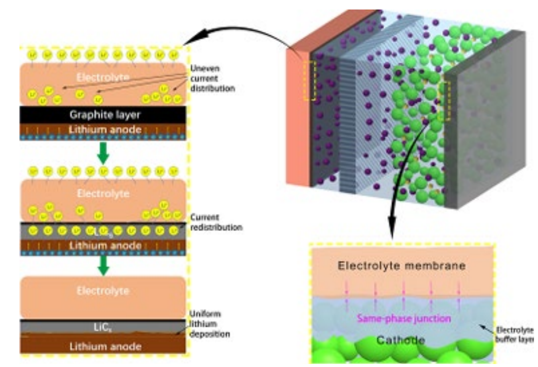
Associate Professor
Mechanical Engineering, ENG
Associate Director
Institute for Global Sustainability

Importance of Interfacial Phenomena

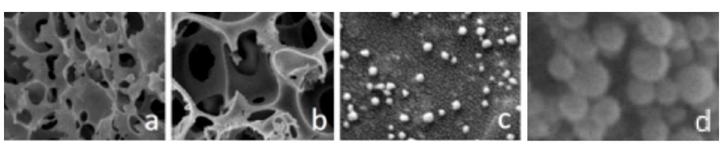
- Drives chemical-physical processes in complex systems
  - Surface reactions for CO_2 capture
  - Electrochemistry in batteries
  - Pollutant adsorption in water filtration
- Challenging to resolve experimentally due to embedded nature
- Not just surface phenomena
  - Mass transport to/through interface
  - Electric fields near interface
  - Structure/surface roughness



Khandaker et al 2020

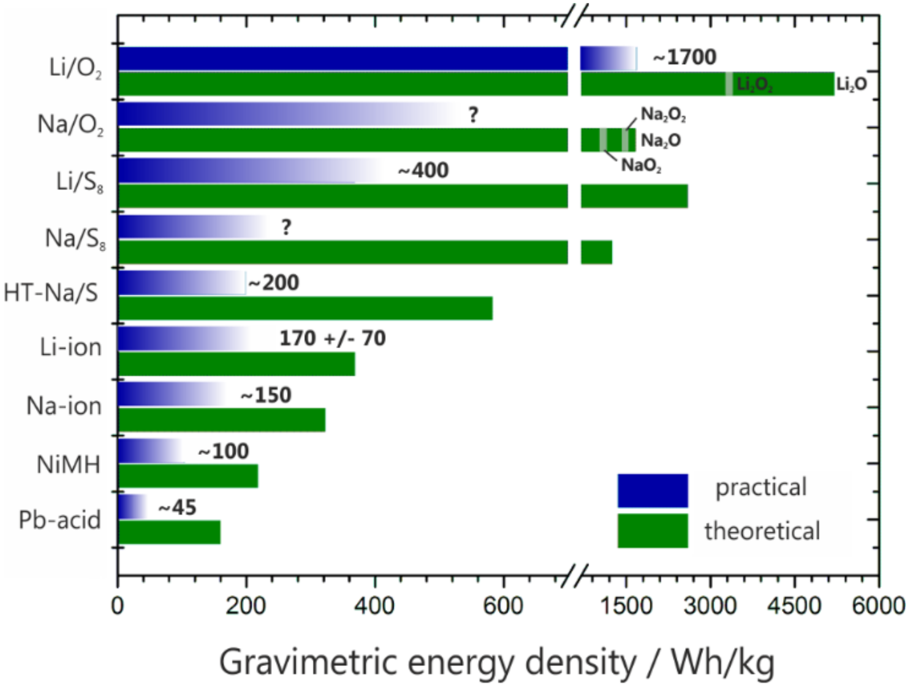


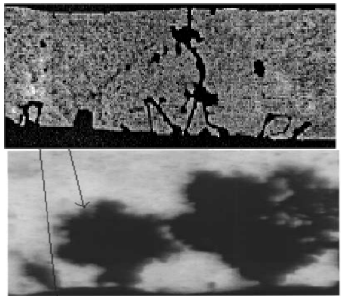
Chen et al 2020



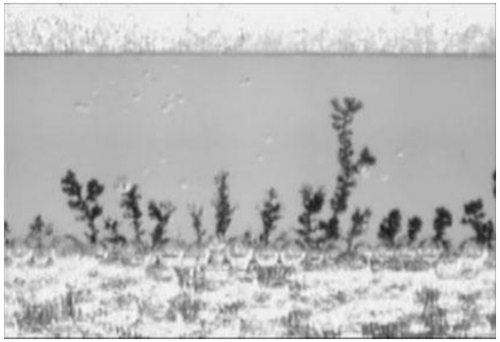
Images from Cornell University

Dendrite Growth in High Energy Density Lithium Batteries

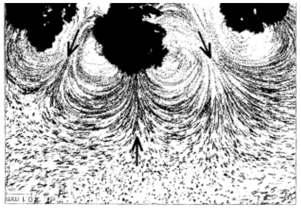




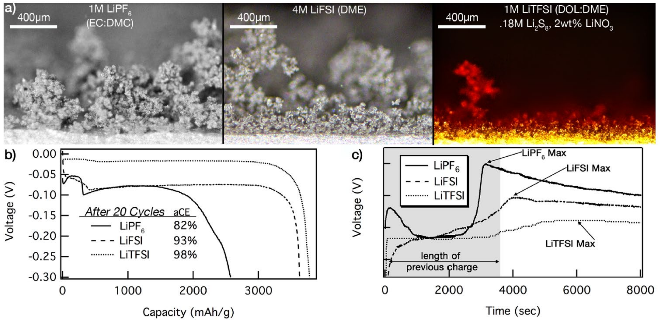
Charge rate effects



Dendrite growth



Electro-osmotic effects



Effects of Electrolyte

Images from: Liu et al 2017; Aqueous Technologies; Brissot et al 1998 and 1999; Huth et al 1995; http://www.extremetech.com/mobile/217191-new-lithium-air-battery-could-drive-huge-performance-gains

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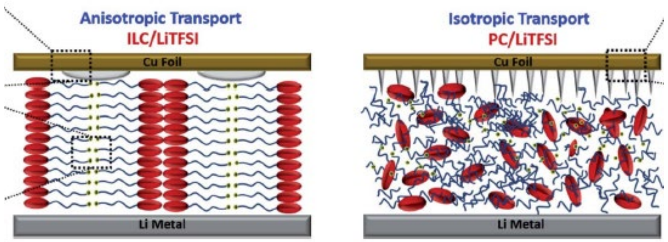
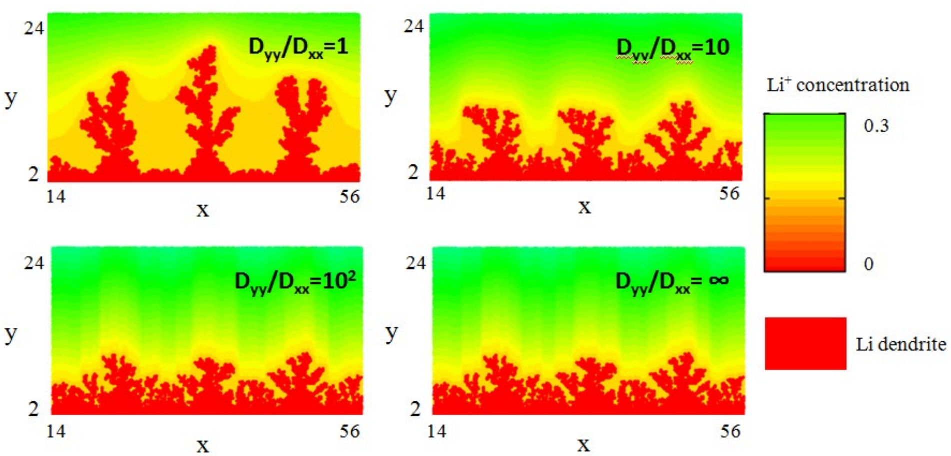
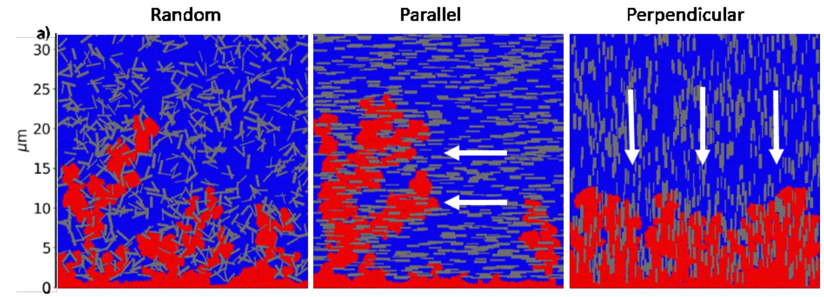
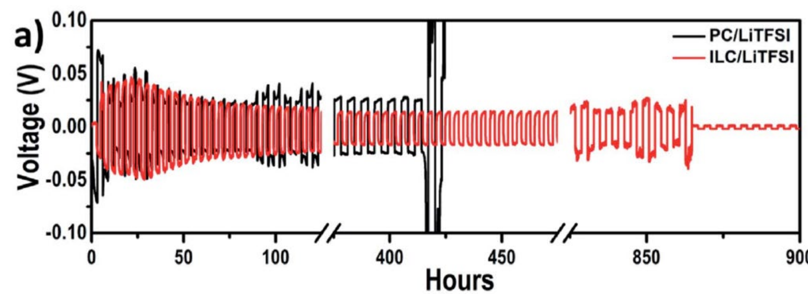
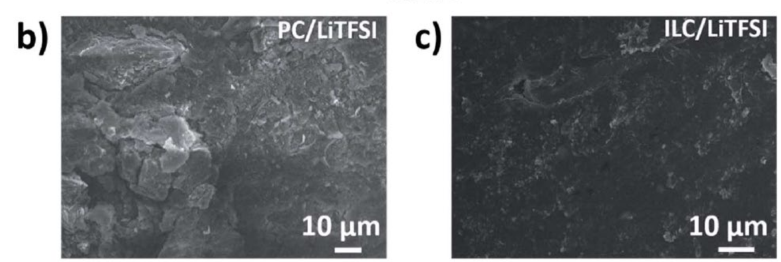
Controlling Dendrites: Anisotropic Ionic Liquid Crystal Electrolytes







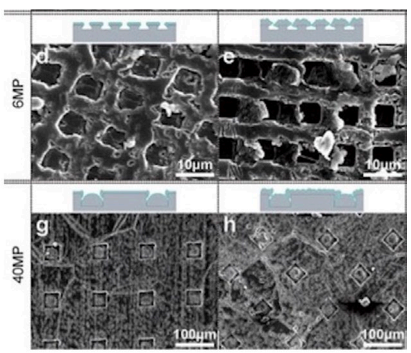


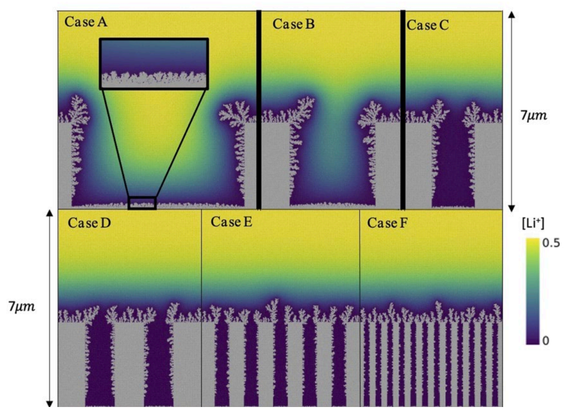


Gopalakrishnan, D., Alkatie, S., Cannon, A., Bhagirath, N., Ryan, E. M. & Reddy Arava, L. M. *Sustainable Energy & Fuels* **5,** 1488–1497 (2021).

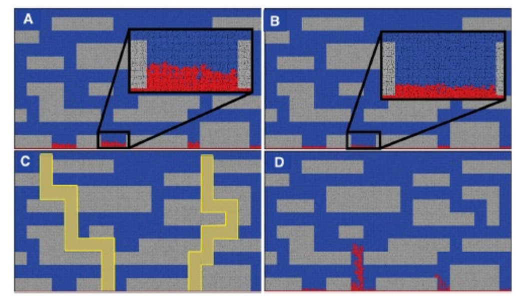
Controlling Dendrites: Structure, Surface Energy, Charging Protocols and more

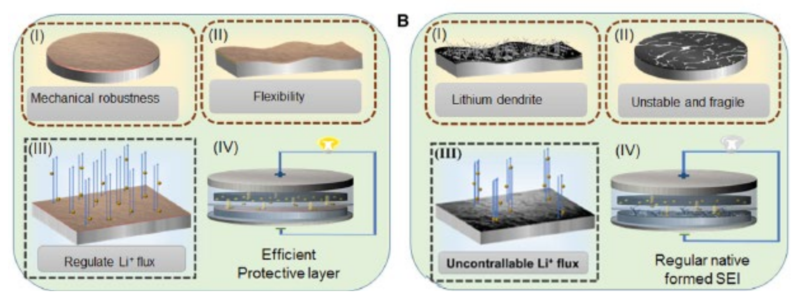
- Collaborating with experimentalists to study methods of dendrite suppression
- Considering: fundamental material behavior, new materials, novel separator designs, charging protocols, effects of surface energy, solid state batteries, …



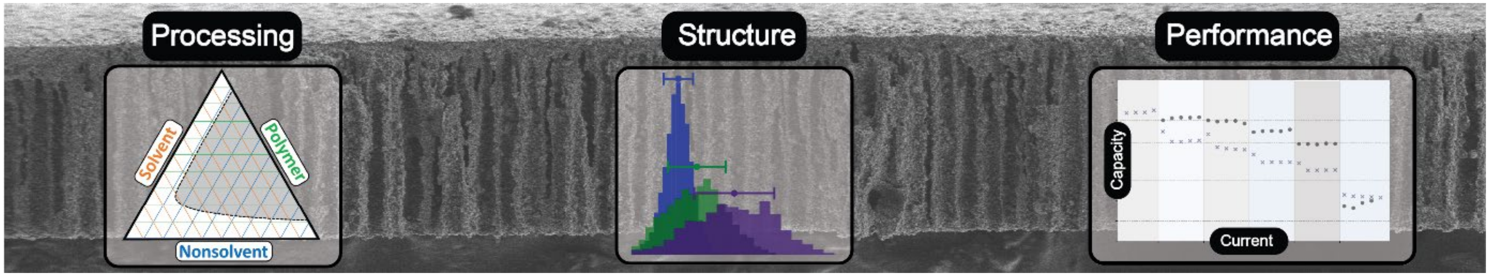


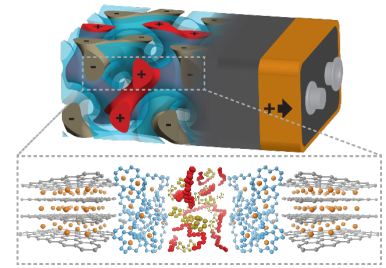
Morey, M., Loftus, J., Cannon, A. & Ryan, E. *The Journal of Chemical Physics* **156,** 14703 (2021).





Gao, S., Cannon, A., Sun, F., Pan, Y., Yang, D., Ge, S., Liu, N., Sokolov, A. P., Ryan, E., Yang, H. & Cao, P.-F. *Cell Reports Physical Science* 100534 (2021).



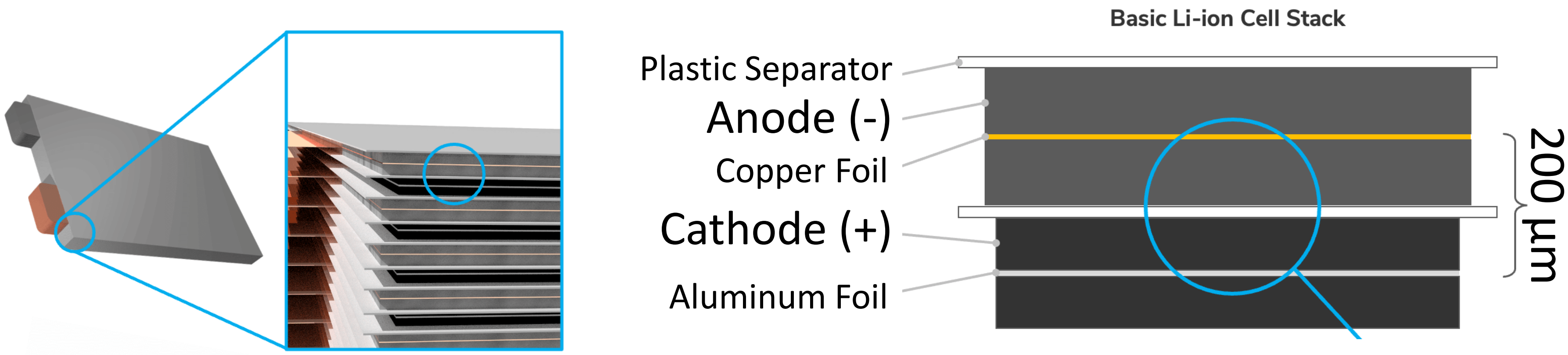


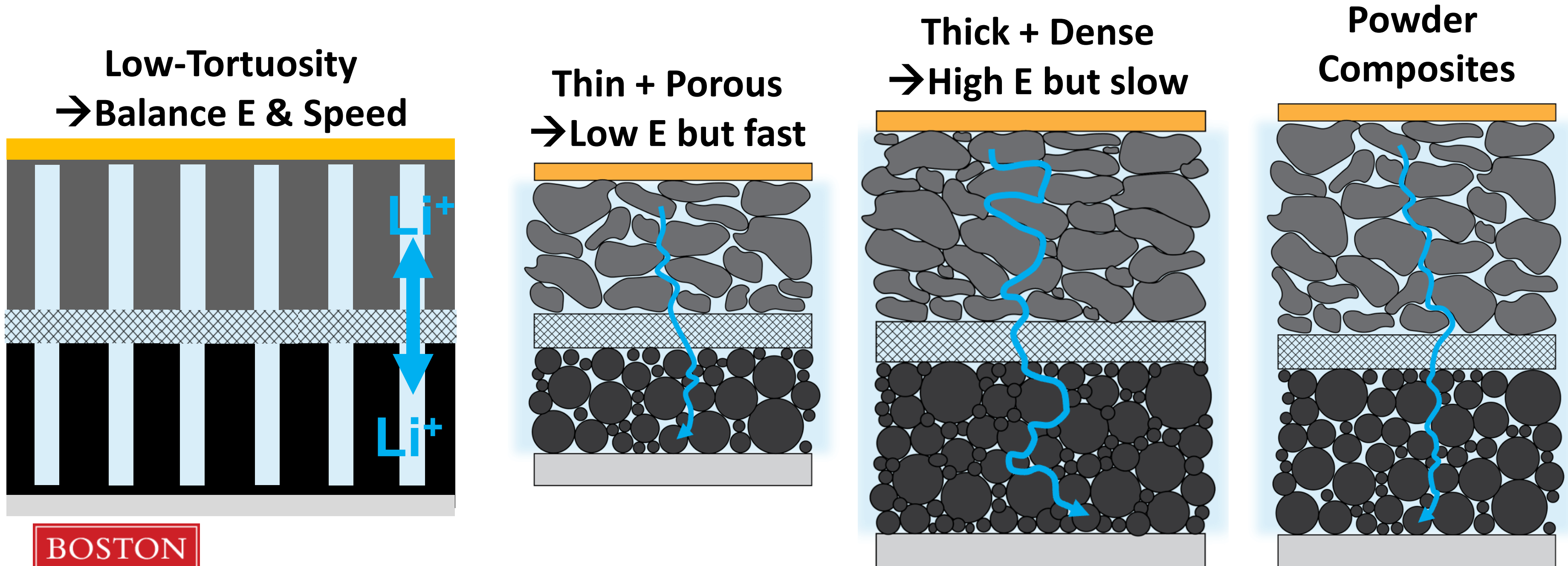
Tailored and Architected Batteries

Jörg Werner, PhD

Assistant Professor
Mechanical Engineering
Division of Materials Science and Engineering
ENG

Balance Energy and Power or Charging Speed

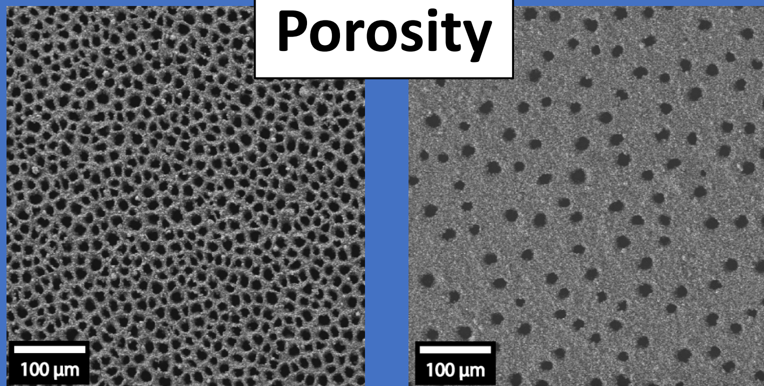


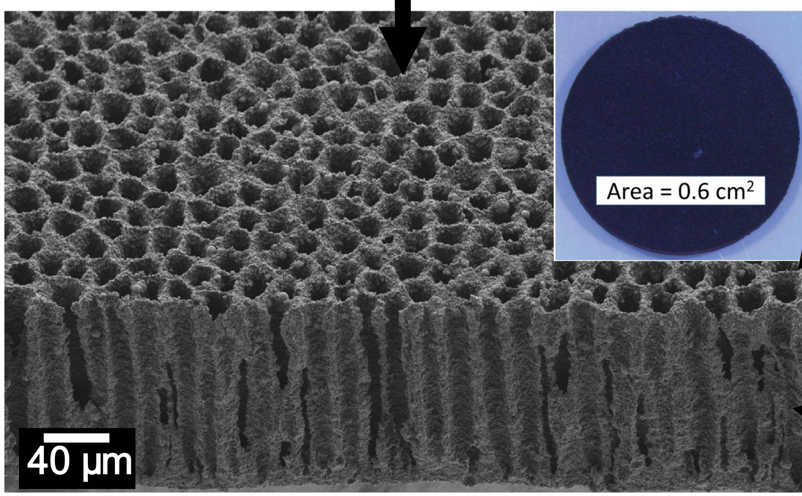


Adapted from: https://honestenergy.substack.com/p/the-little-ion-that-could

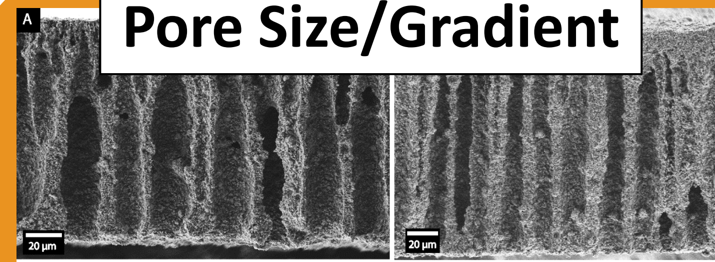
Removing Tortuosity and Tailoring Porosity

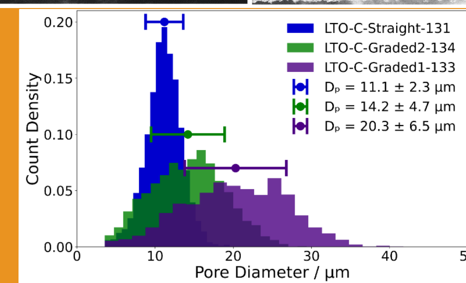
Porosity



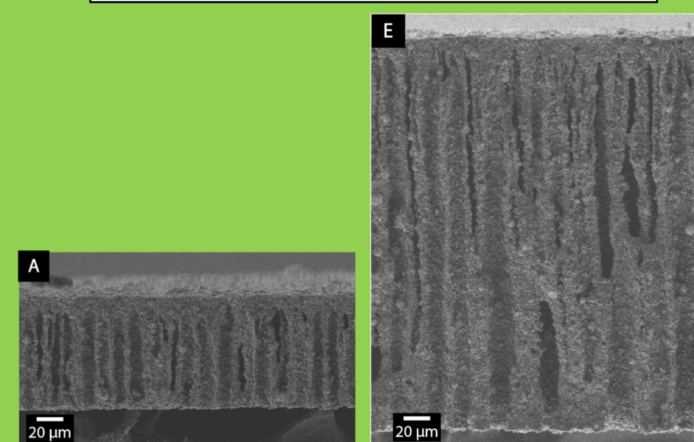


Pore Size/Gradient





Electrode Thickness



Scalable Manufacturing: Phase Inversion

→ water filtration membranes since 1960

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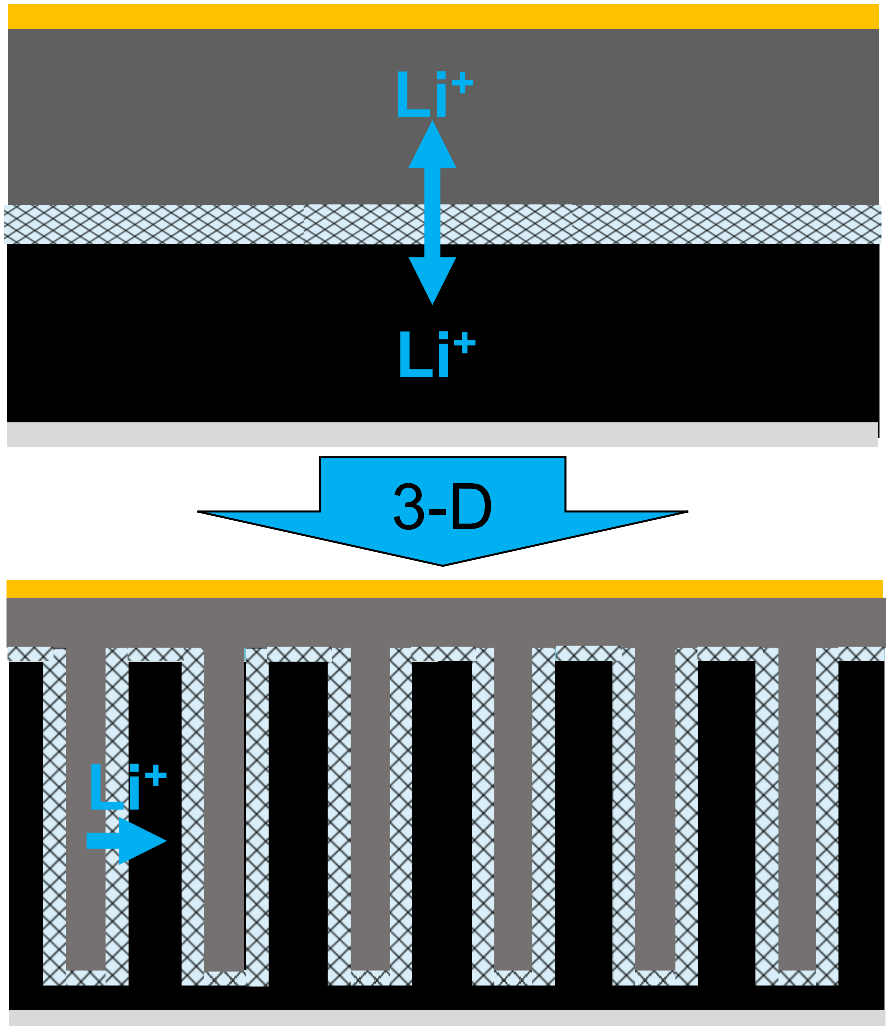
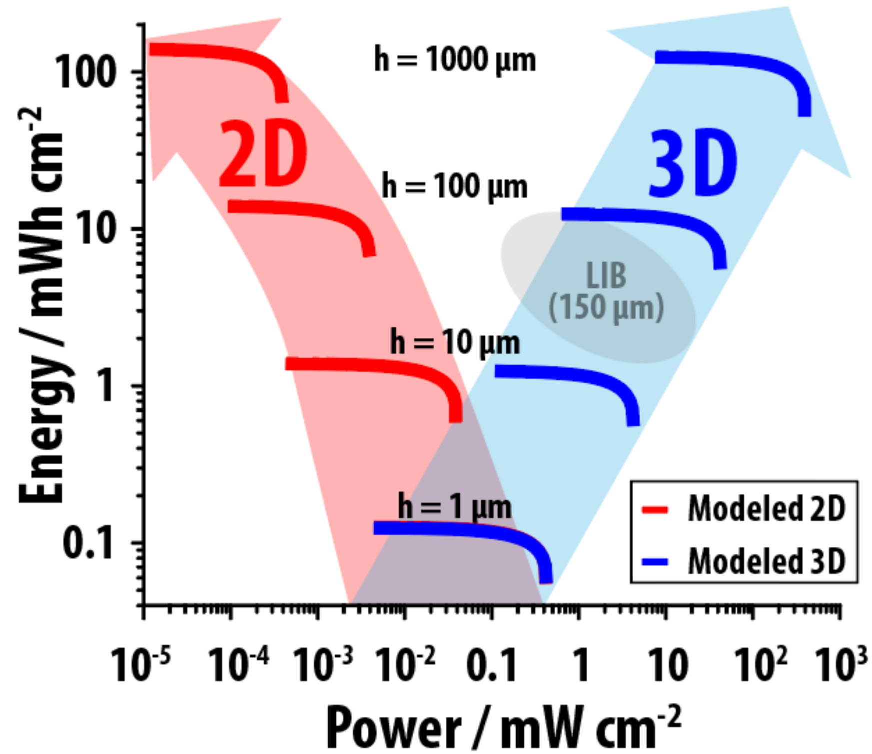
Boston University Office of Research

Resing, Fukuda, Werner, *Advanced Materials* **2022**, ASAP.

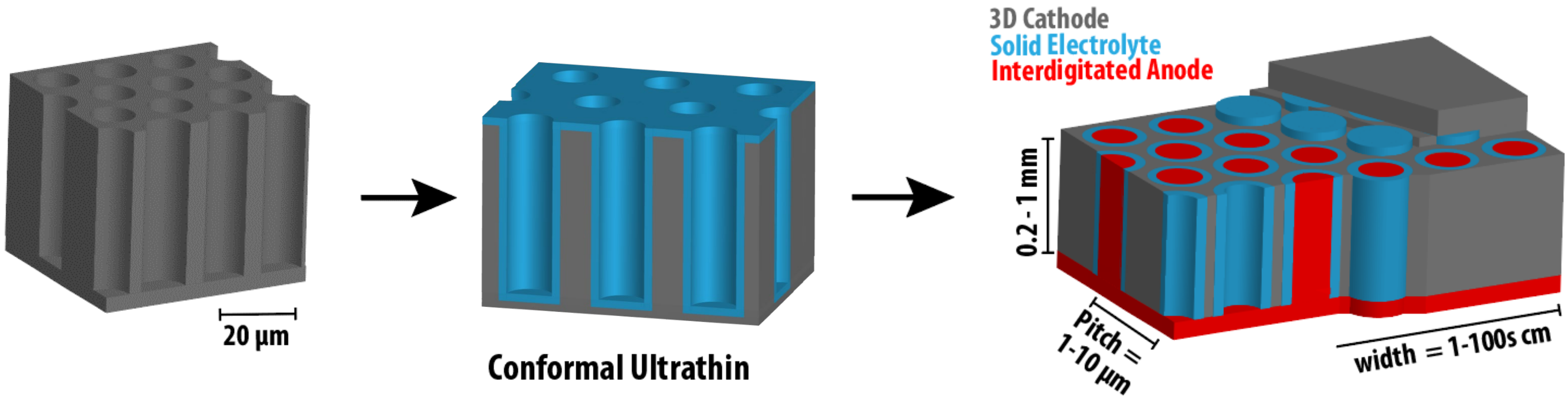
Turning It Outside-In: 3-D Batteries





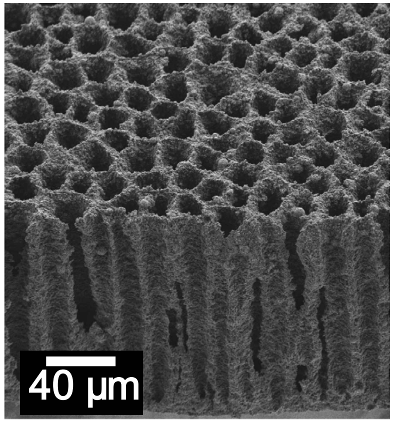
- Short ion-distances: fast
- Independent of cell thickness
- Requires ultrathin separator (<20%)

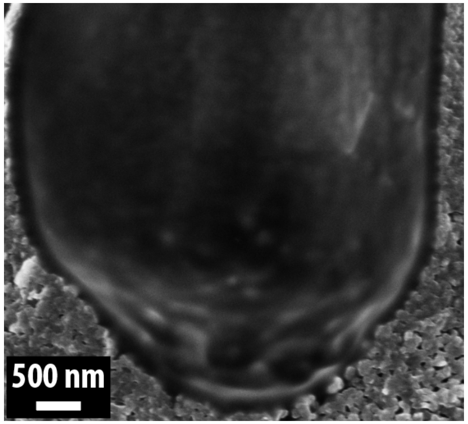
Synthesizing 3-D Batteries from the Bottom Up

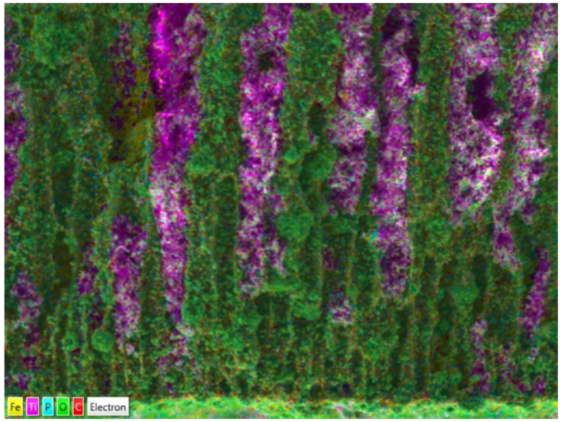


3D Cathode

Conformal Ultrathin Solid Electrolyte







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Boston University Office of Research

Werner *et al.*, *Energy & Environmental Science* **2018**, 11(5), 1261-1270.

Towards Sustainable Computing (and Computing for Sustainability)

Ayse K. Coskun

Professor
Electrical and Computer Engineering, ENG

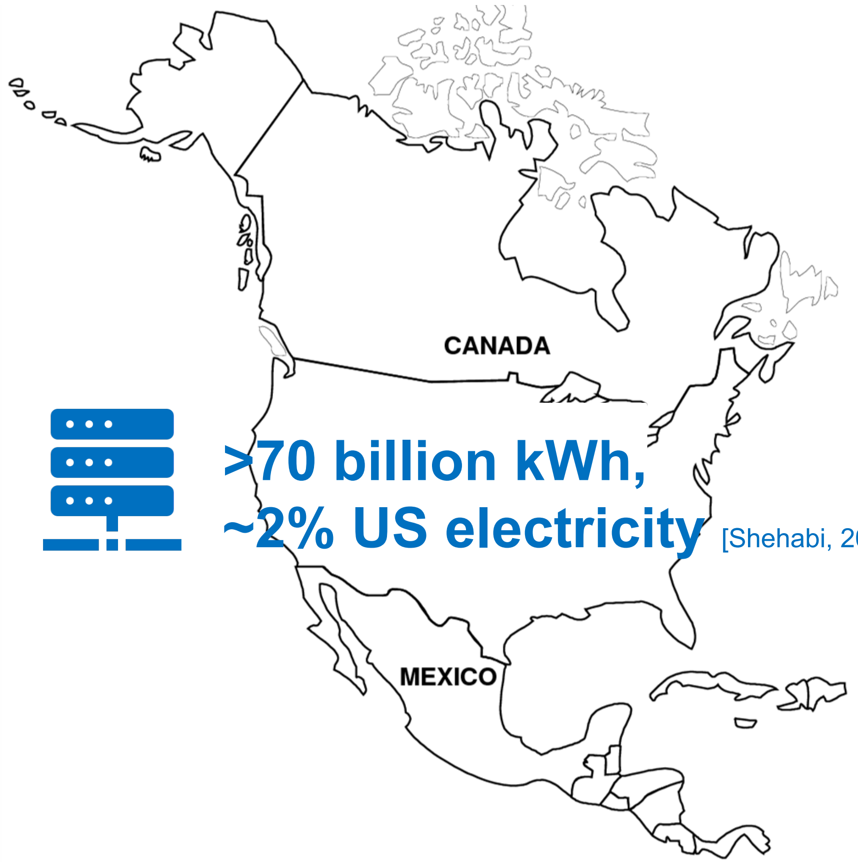
Data Centers and High-Performance Computing (HPC) Systems

Data analysis

Cloud Services

Scientific Simulations

etc.



>70 billion kWh, ~2% US electricity [Shehabi, 2016]

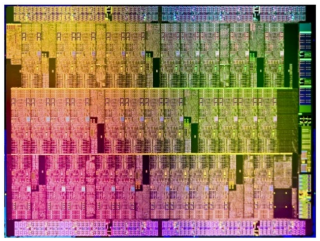
Fugaku
Top Supercomputer
Peak Power: 29 MW
Electricity cost:
$100,000+/day

[Shehabi, 2016] A. Shehabi, et al. United states data center energy usage report. Lawrence Berkeley National Laboratory. LBNL-1005775, 2016.

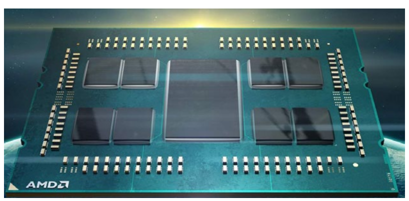
Designing (more) efficient computers

Chips today

Intel Xeon Phi (2015)

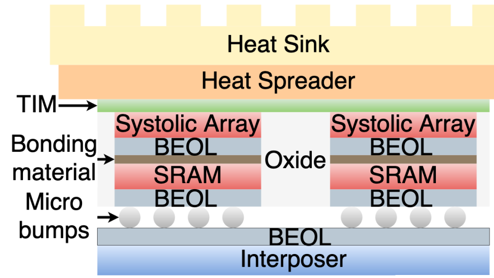


AMD EPYC Rome (2019)



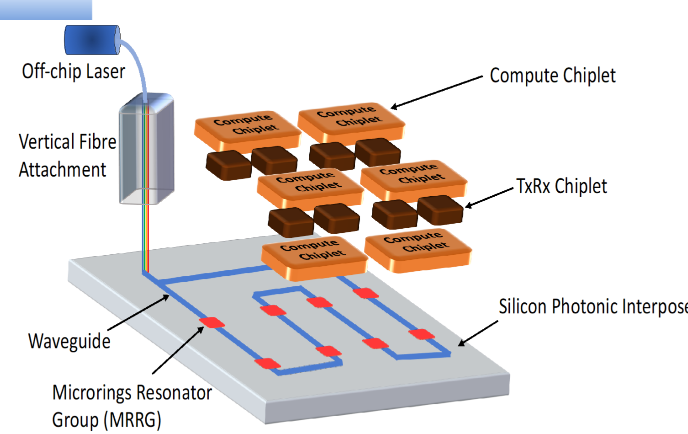
Nvidia Grace AI (2021)

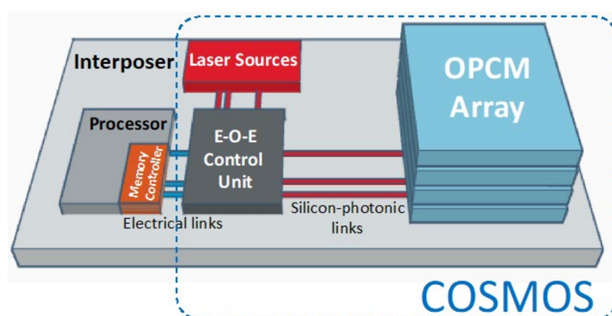
Chips of the near(?) future



3D-stacked "chiplet"s on an interposer

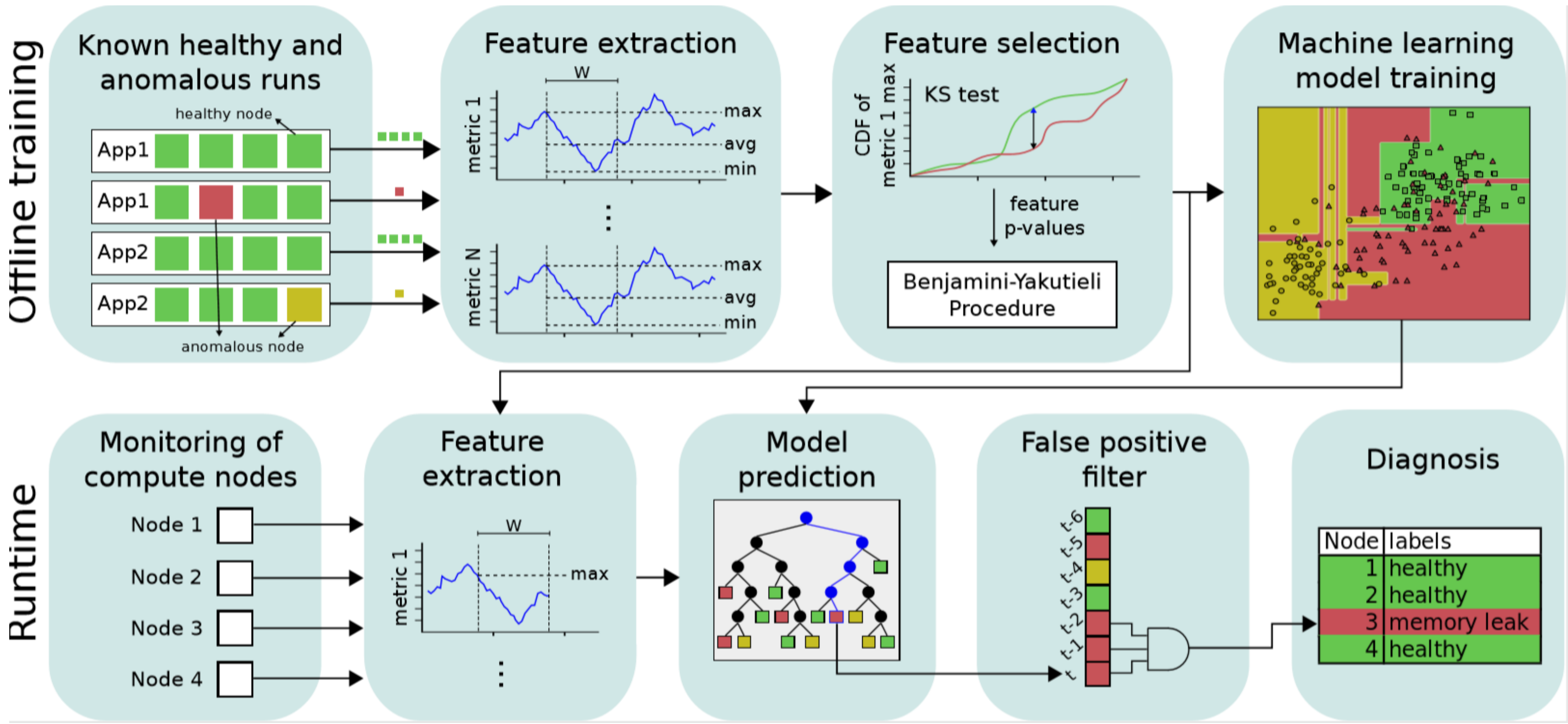
2.5D manycore chip with silicon-photonic links





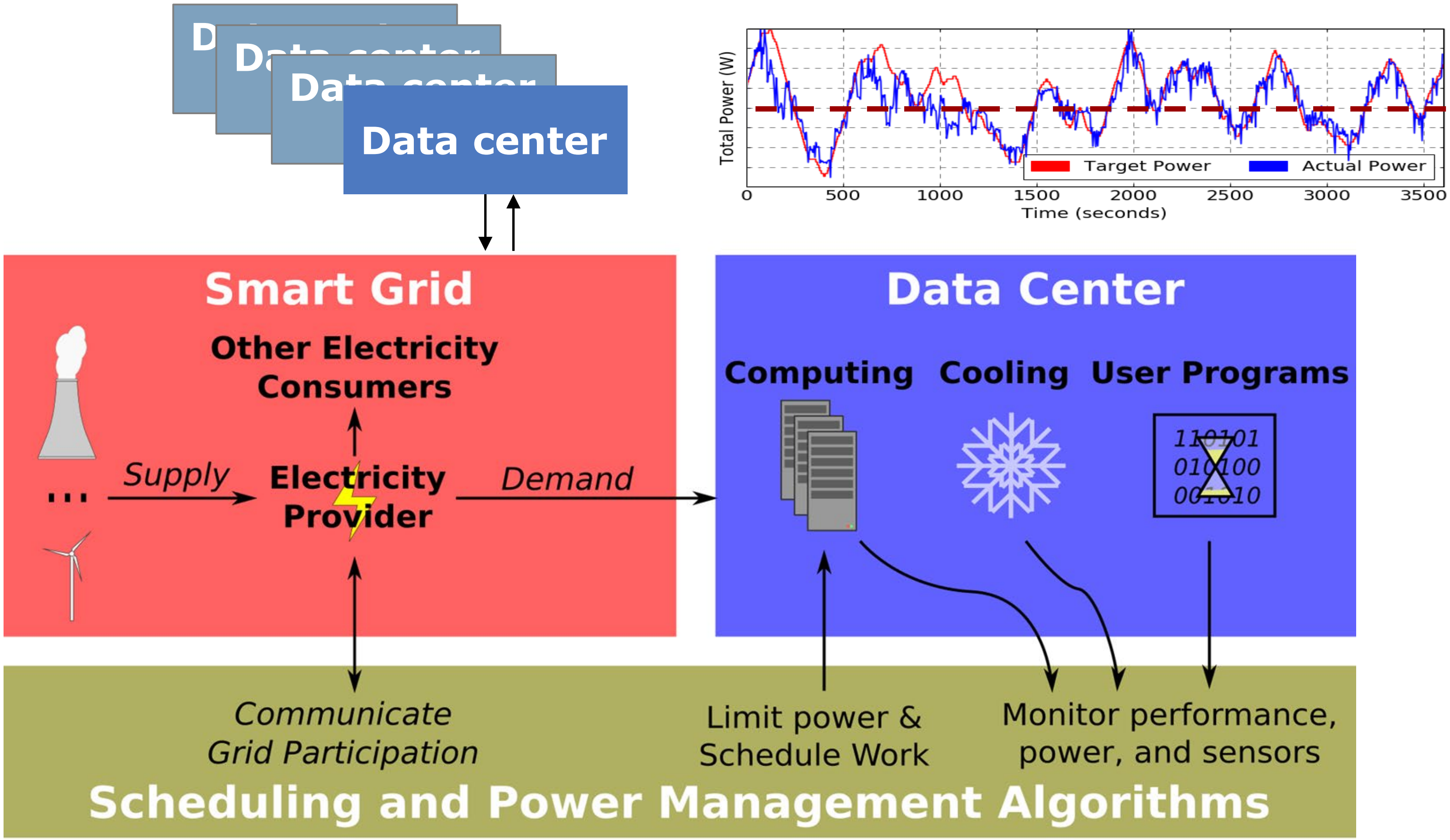
A combined system of optically-addressed phase-change memory and optical links

Diagnosing inefficiencies … efficiently!



- PeacLab's ML-based performance diagnostics software: https://github.com/peaclab/ALBADross
- AI for Cloud Ops: https://research.redhat.com/blog/research_project/ai-for-cloud-ops/

Computing for sustainability



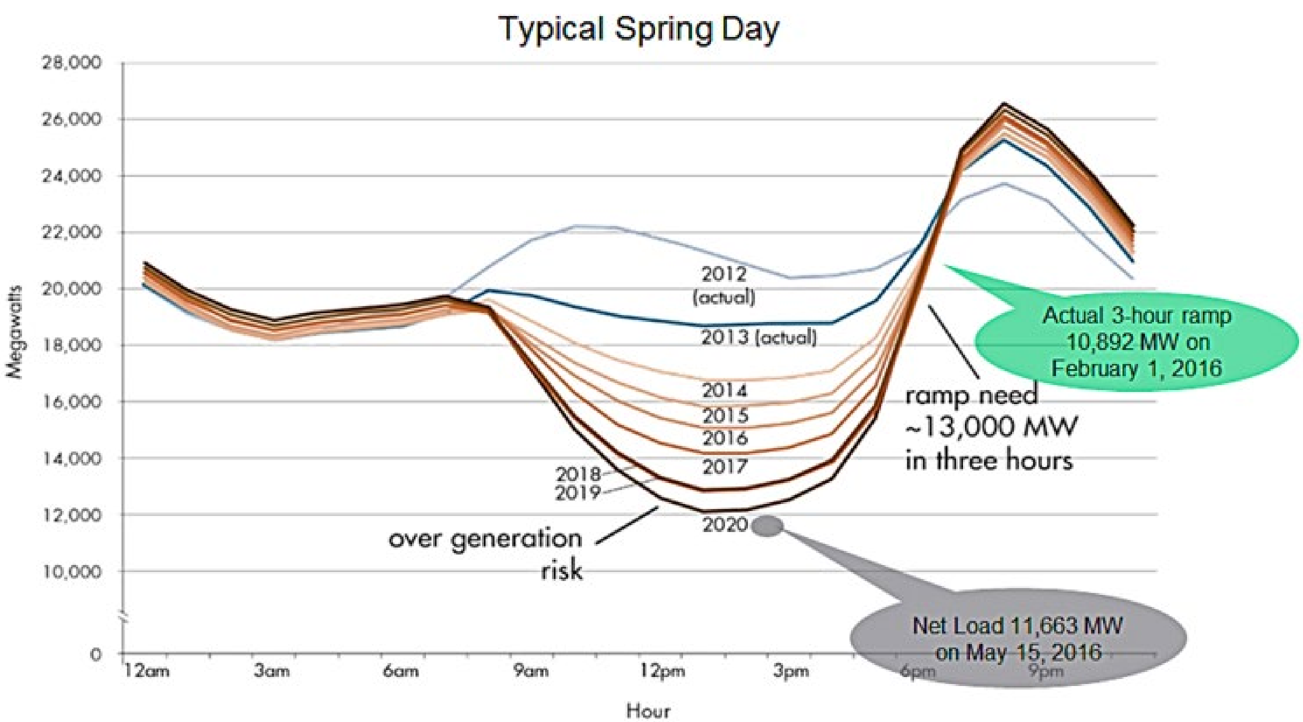
Grid Scale Renewable Energy Storage: A Case for Reversible Solid Oxide Cells

Srikanth Gopalan

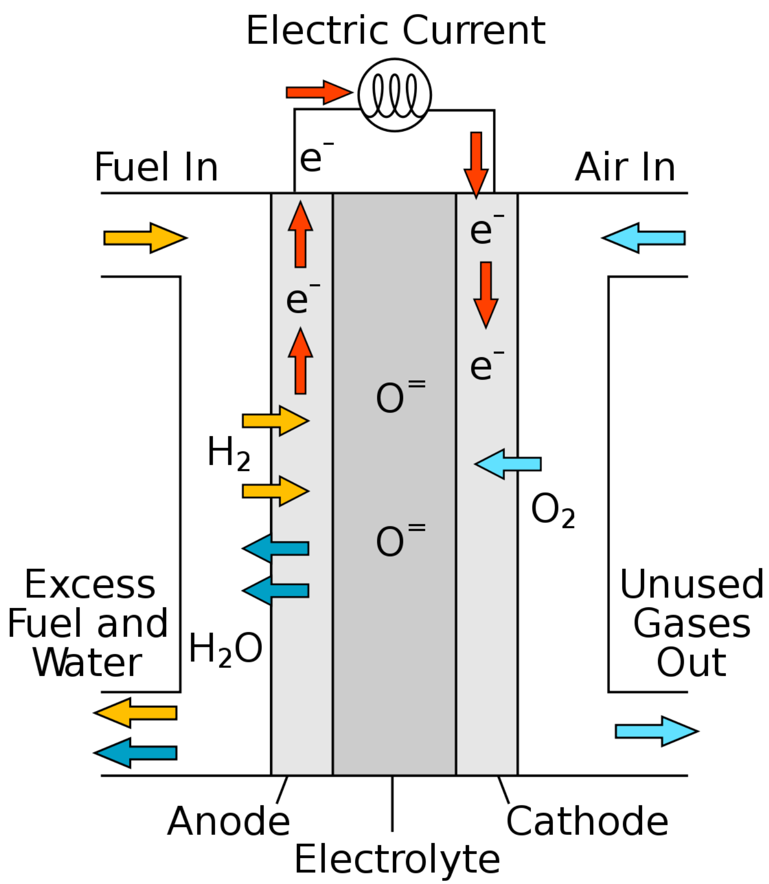
Associate Professor
Materials Science and Engineering
Mechanical Engineering
ENG
Email: sgopalan@bu.edu

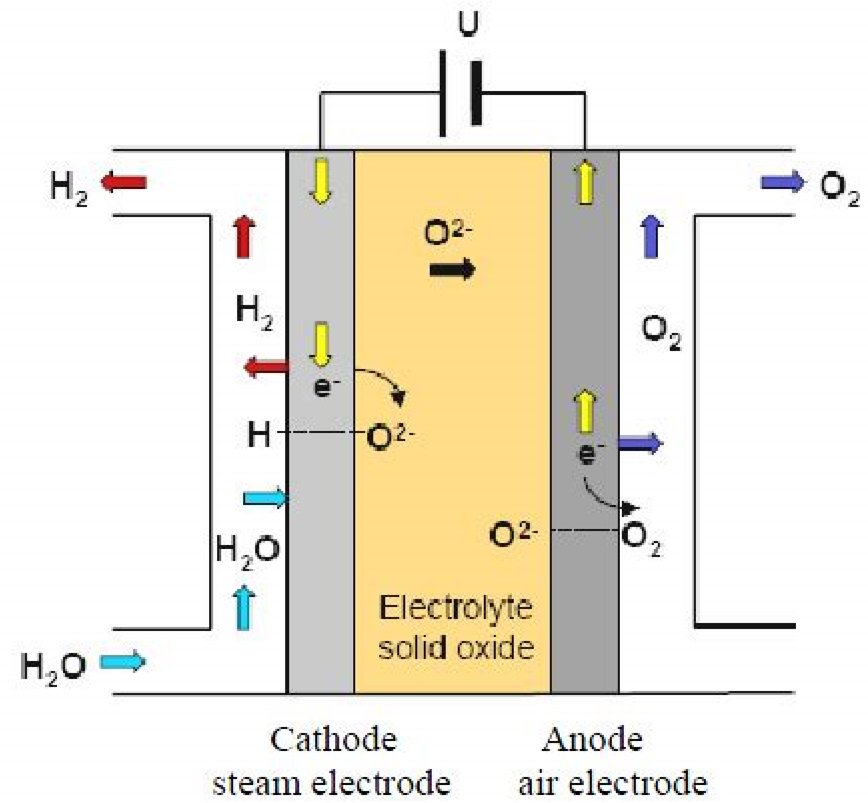
Ramp Requirements During Peak Power

Figure 2: The duck curve shows steep ramping needs and overgeneration risk

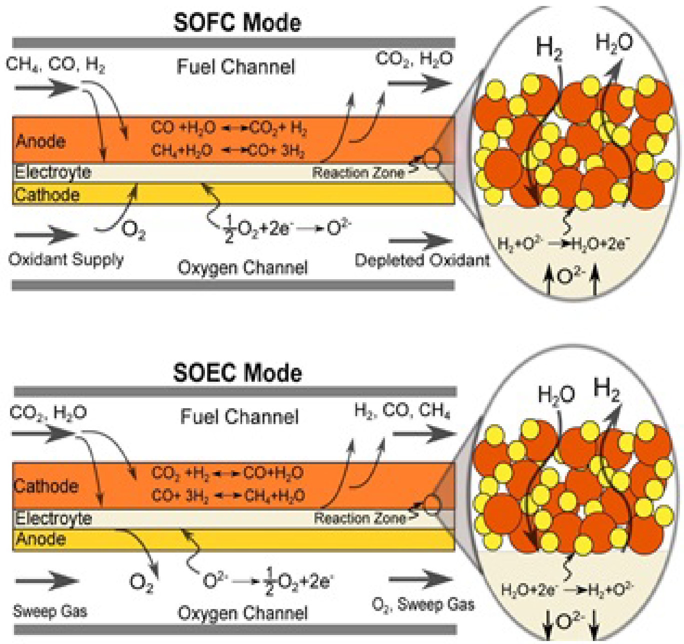


Solid Oxide Fuel Cells (SOFC) and Electrolysis Cells (SOECs)

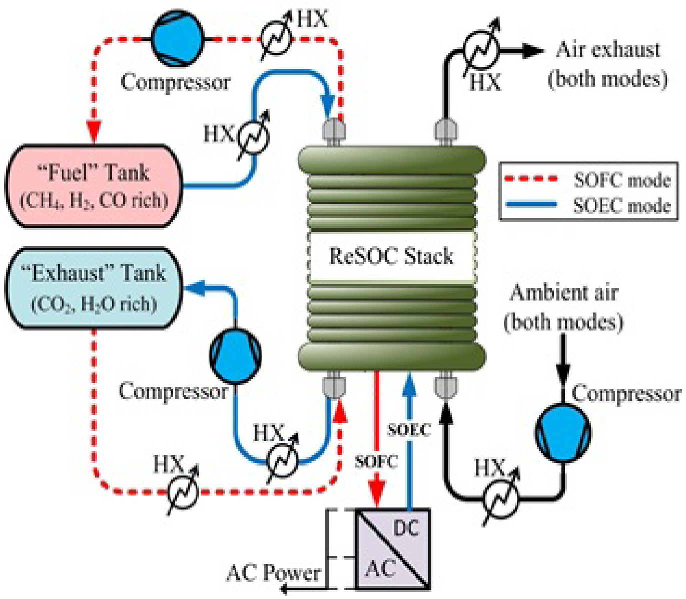




Solid Oxide Cells Can Address this!



Reversible solid oxide cell operation



Simplified schematic of a ReSOC electrical energy storage system

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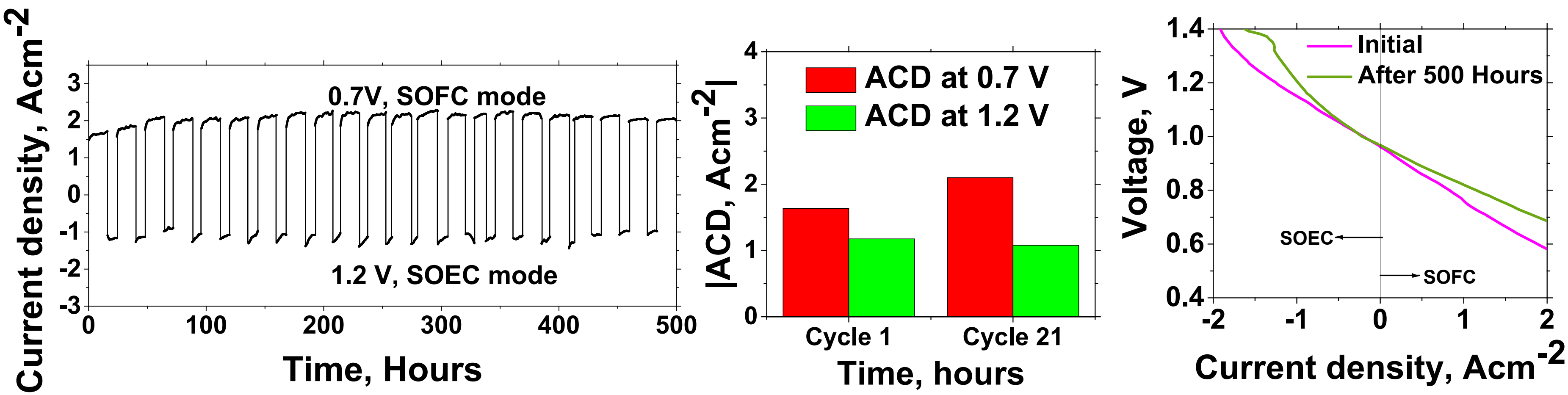
Boston University Office of Research

Cycling from Storage (Electrolysis) to Generation (Fuel Cells)



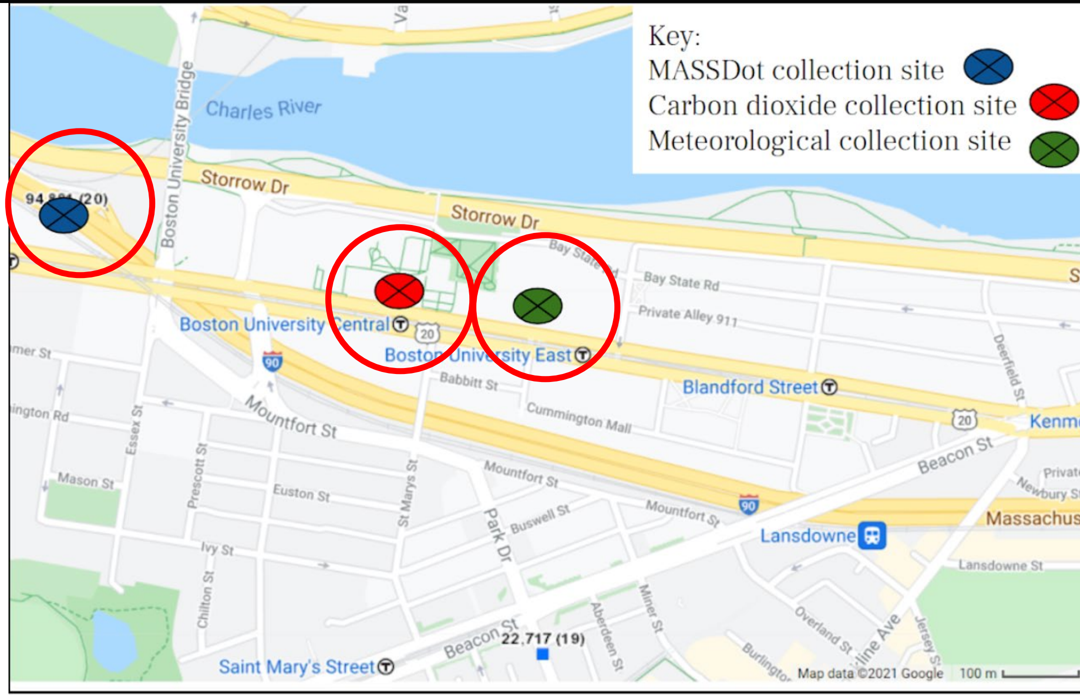
- Challenges: Addressing degradation – interfaces, interfaces, interfaces!

The Many Disciplines of Sustainability

Robert K. Kaufmann

Professor
Earth & Environment
CAS

A local effect of carbon dioxide on temperature?



- There is an hourly relation
- What causes the relation?
  - Waste heat
  - Increased stomatal resistance reduces evapotranspiration
  - Local greenhouse effect increases absorption outgoing short wave
- Diurnal and seasonal relations
  - Relation strongest at night when stomates are closed
  - Relation present during winter when no leaves

Energy distributive justice: Who lost power in Texas during the 2021 winter storm?

Hypothesis #1 Disruptions in T&D reduce the need to allocate load shed. Yes method separates load shed

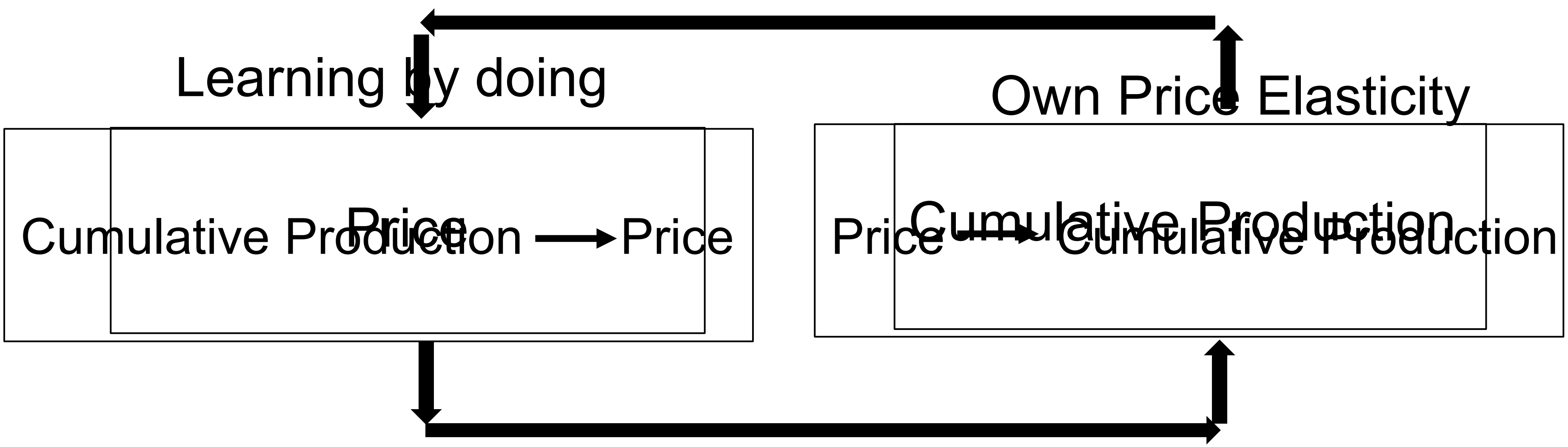
Hypothesis #2 Providers preferentially allocate load shed to counties where a large percentage of residents have low levels of income or wealth. Mixed

Hypothesis #3 Providers preferentially allocate load shed to counties where a large percentage of residents are members of underrepresented groups. Yes

More than fair share Hispanic, African American, Asian

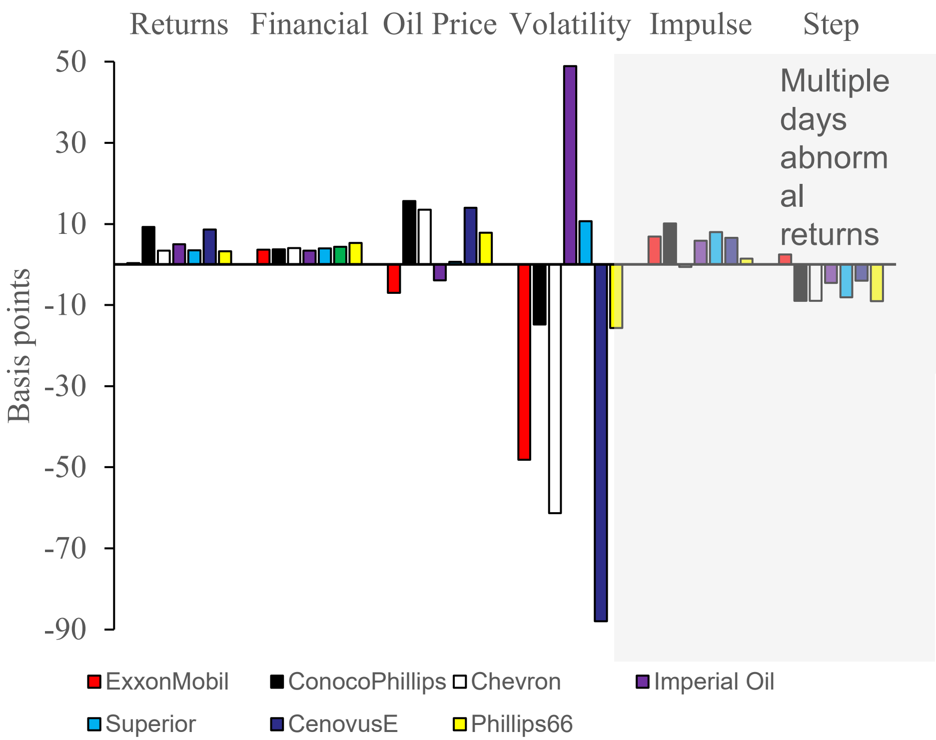
Less than fair share; White

A learning by doing multiplier accelerates time to grid parity PV

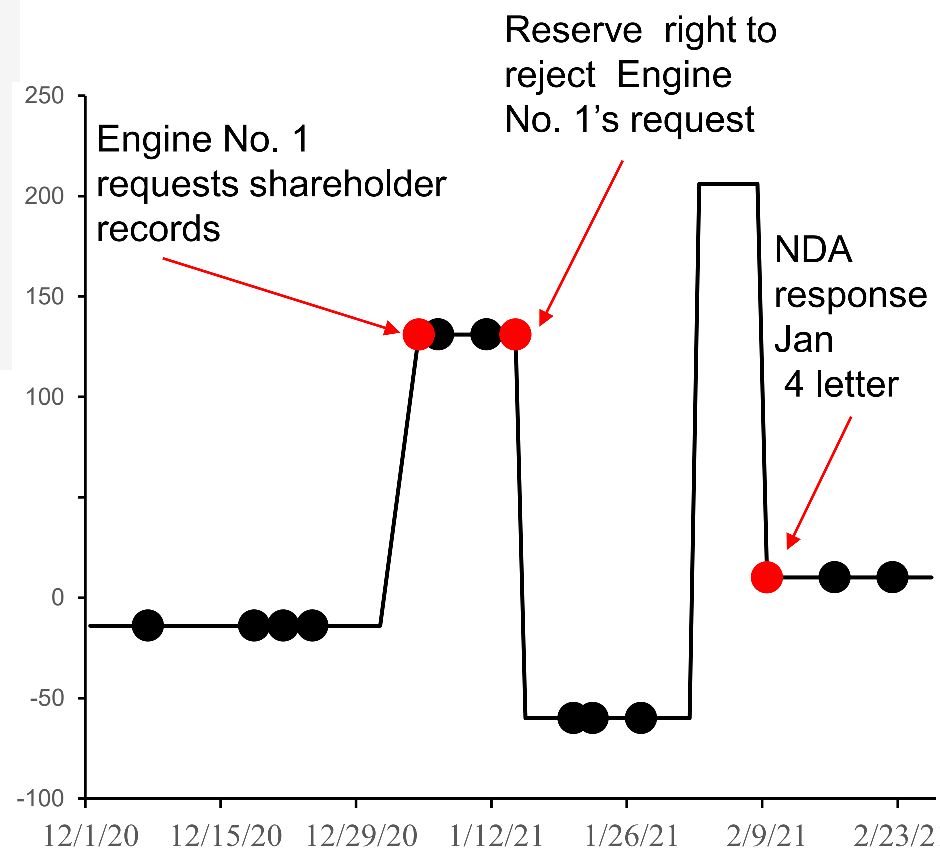


- Multiplier effect
  - Increases income effect by 10x
  - Carbon price 16x

Hedge Fund Activism: Engine No. 1 & ExxonMobil



Efforts by Engine 1 generate abnormal returns but electing board members does not



Poor performance not caused by mismanaging climate risk.

Equity, Justice, and Low-Carbon Technology

Benjamin K. Sovacool

Director, Institute for Global Sustainability
Professor, Earth and Environment, CAS

A matrix of inequities and vulnerabilities with low-carbon tech

Demographic inequity (between groups)	**Spatial inequity (across geographical scales)**
· Adoption is strongly mandated by gender roles (EVs, improved cookstoves, food-sharing) · Diffusion patterns substantially shaped by class, caste, income or wealth (improved cookstoves, EVs, solar panels, food-sharing) · Exclusion of non-homeowners or those without access to roofs (solar panels) · Adoption patterns favouring wealthier households and communities of mainly white people, and disfavouring those struggling with illness or financial difficulty (solar panels) · Subsidies favouring wealthier households (EVs, solar panels) · Adoption patterns favouring higher-income homes, larger homes and homes with children (food-sharing) · May entrench inequality and a gap in digital skills and awareness (food-sharing) · Can put those with food allergies or special needs at risk of contamination or illness (food-sharing) · Depends on a relatively advanced skillset of food preparation, handling, storage and refrigeration as well as disposal and waste (food-sharing)	· Erodes some spiritual and cultural practices in rural communities (for improved cookstoves) · Threatens rural food preservation based on smoke where alternatives are unavailable (for improved cookstoves) · Contributions to traffic congestion and automobile accidents in cities (EVs) · Lack of charging infrastructure in rural areas (EVs) · Perpetuation of a 'decarbonization divide' between Global North and Global South (EVs, solar panels) · Shifting of conventional cars to peripheral (non-low-carbon) areas (EVs) · Cross-subsidization of energy costs that burden the poor (solar panels) · Unfair and at times exploitative labour practices (solar panels) · Bias towards urban areas and cities, less rural states, and especially wealthier cities and cities in the Global North (food-sharing, solar panels)
Interspecies inequity (between humans and non-humans)	**Temporal inequity (across future generations)**
· Rebounds in increased driving or kilometres travelled impinging on forests or nature reserves (EVs) · Roadbuilding and impingement of green spaces or trees in urban areas (EVs) · Pushing of conventional cars to peripheral regions increasing air and water pollution (EVs) · Increased air pollution or carbon emissions from fossil-fuelled electricity (EVs) · Electronic waste streams releasing toxics into habitats (solar panels and EVs) · Environmental destruction and deforestation with mineral and material extraction (EVs and solar panels) · Fossil-fuel use, occupational hazards and pollution from local manufacturing (solar panels) · Potential rebounds in increased waste (and toxins) due to mistakes and improper sorting or handling (food-sharing)	· Embedding private motorized automobility for future generations (EVs) · Failing to address the underlying causes of food waste and unsustainable agriculture (food-sharing) · Cementing future burden of cooking and domestic activities onto women (for improved cookstoves) · Generation of toxic waste streams and disposal concerns for future generations (EVs, solar panels) · For-profit motivations can lead to conflict and community tension over future food pathways and limit sustainable change (food-sharing) · Can legitimize overproduction and food surplus and fail to address the root causes of food insecurity (food-sharing)

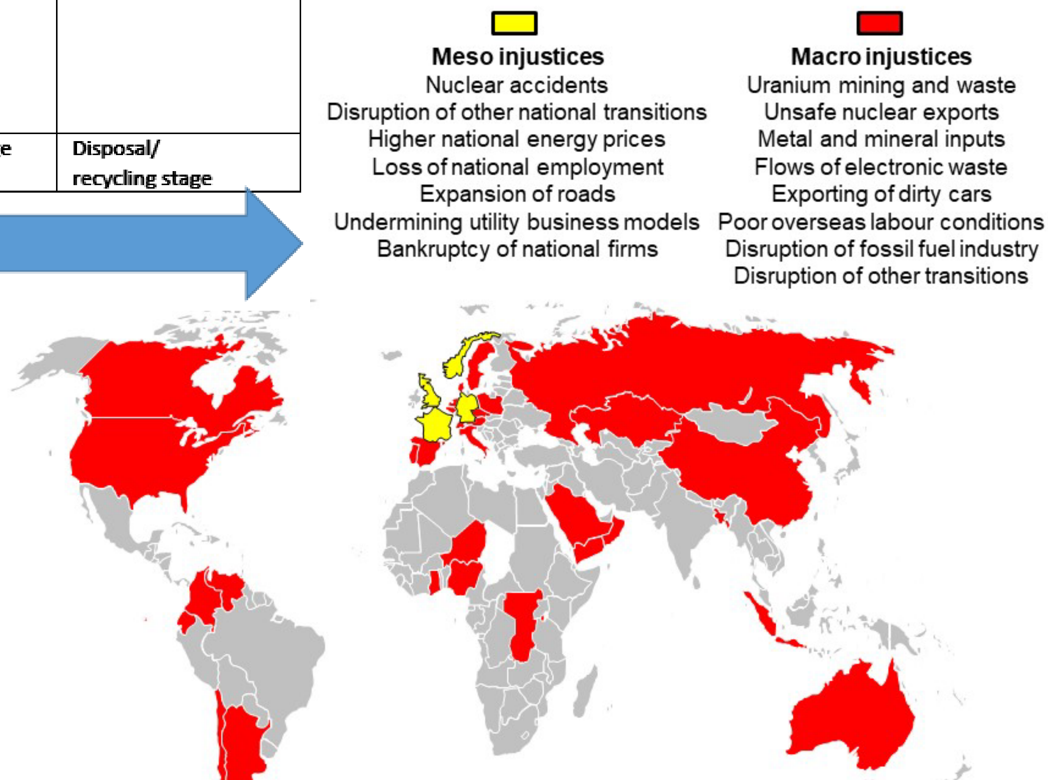
Source: Sovacool, B.K., Newell, P., Carley, S. et al. Equity, technological innovation and sustainable behaviour in a low-carbon future. *Nat Hum Behav* (2022). https://doi.org/10.1038/s41562-021-01257-8

Justice impacts through a “whole-systems” lens

Spatial

Macro scale (global)	• Mineral extraction processes • Transportation of materials • Labor conditions • Global supply chains	• Rising energy demand • Impact on other countries’ policies	• Rising global waste • Geopolitical issues
Meso scale (national)	• Increase in subsidies leading to raised taxes • Carbon footprint of installations • Diversion of funds from other sectors	• Inequality of benefits • Increased vulnerability and inequality	• Waste • Costs of disposal • Recycling of old materials
Micro scale (local)	• Disruption of ecosystems • Diversion of funds from other sectors • Loss of local jobs in old systems • Health risks to workers in factories	• Local pollution • Exposure to local risks • Urban-rural divide	• Legacy of local pollution
	Production/ distribution stage	**Consumption stage**	**Disposal/ recycling stage**

Temporal



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Energy impacts often befall the *most* vulnerable groups

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Energy impacts often befall the *most* vulnerable groups

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Review

Who are the victims of low-carbon transitions? Towards a political ecology of climate change mitigation

Benjamin K. Sovacool [a,b,*]

Abstract

This study critically examines 20 years of geography and political ecology literature on the energy justice implications of climate change mitigation. Grounded in an expert guided literature review of 198 studies and their corresponding 332 case studies, it assesses the linkages between low carbon transitions—including renewable electricity, biofuel, nuclear power, smart grids, electric vehicles, and land use management—with degradation, dispossession and destruction. It draws on a framework that envisions the political ecology of low-carbon transitions as consisting of four distinct processes: enclosure (capture of land or resources), exclusion (unfair planning), encroachment (destruction of the environment), or entrenchment (worsening of inequality or vulnerability). The study vigorously interrogates how these elements play out by country and across countries, by type of mitigation option, by type of victim or affected group, by process, and by severity, e.g. from modern slavery to organized crime, from violence, murder and torture to the exacerbation of child prostitution or the destruction of pristine ecosystems. It also closely examines the locations, disciplinary affiliations, methods and spatial units of analysis employed by this corpus of research, with clear and compelling insights for future work in the space of geography, climate change, and energy transitions. It suggest five critical avenues for future research: greater inclusivity and diversity, rigor and comparative analysis, focus on mundane technologies and non-Western case studies, multi-scalar analysis, and focus on policy and recommendations. At times, low-carbon transitions and climate action can promote squalor over sustainability and leave angry communities, disgruntled workers, scorned business partners, and degraded landscapes in their wake. Nevertheless, ample opportunities exist to make a future low-carbon world more pluralistic, democratic, and just.

Table 3
Vulnerable groups mentioned in academic research on political ecology and climate mitigation (n = 198 studies).

Vulnerable group	No. of articles	% of articles
Non-human species	153	77.3%
Local communities, host communities, adopters or households	152	76.8%
Farmers, agriculturalists, or pastoralists	74	37.4%
Rural poor	73	36.9%
Occupational workers, wage laborers, or their unions	72	36.4%
Indigenous/aboriginal groups, ethnic/racial minorities, or members of a lower caste	71	35.9%
Future generations (e.g., nuclear waste)	71	35.9%
Fishers and water resource users	51	25.8%
Environmental groups, civil society, wildlife reservists, land managers or nature conservationists	38	19.2%
Urban poor	36	18.2%
Women (including gender roles)	27	13.6%
Recreationists, campers, hikers, forest users	27	13.6%
Banks, financiers, investors (including fossil fuel incumbents)	27	13.6%
Elderly	13	6.6%
Students	13	6.6%
Disabled individuals	12	6.1%
Forced labor or modern slaves	10	5.1%
Coastal homeowners (e.g. offshore wind energy)	10	5.1%
Prostitutes	10	5.1%
Children or youth (including health impacts)	5	2.5%
Local businesses (including tourism)	5	2.5%
Refugees (including displaced persons and forced migrants)	3	1.5%
Alcoholics	3	1.5%
Affluent suburban homeowners	1	0.5%

Source: Author.

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