Decarbonization Research Consortium

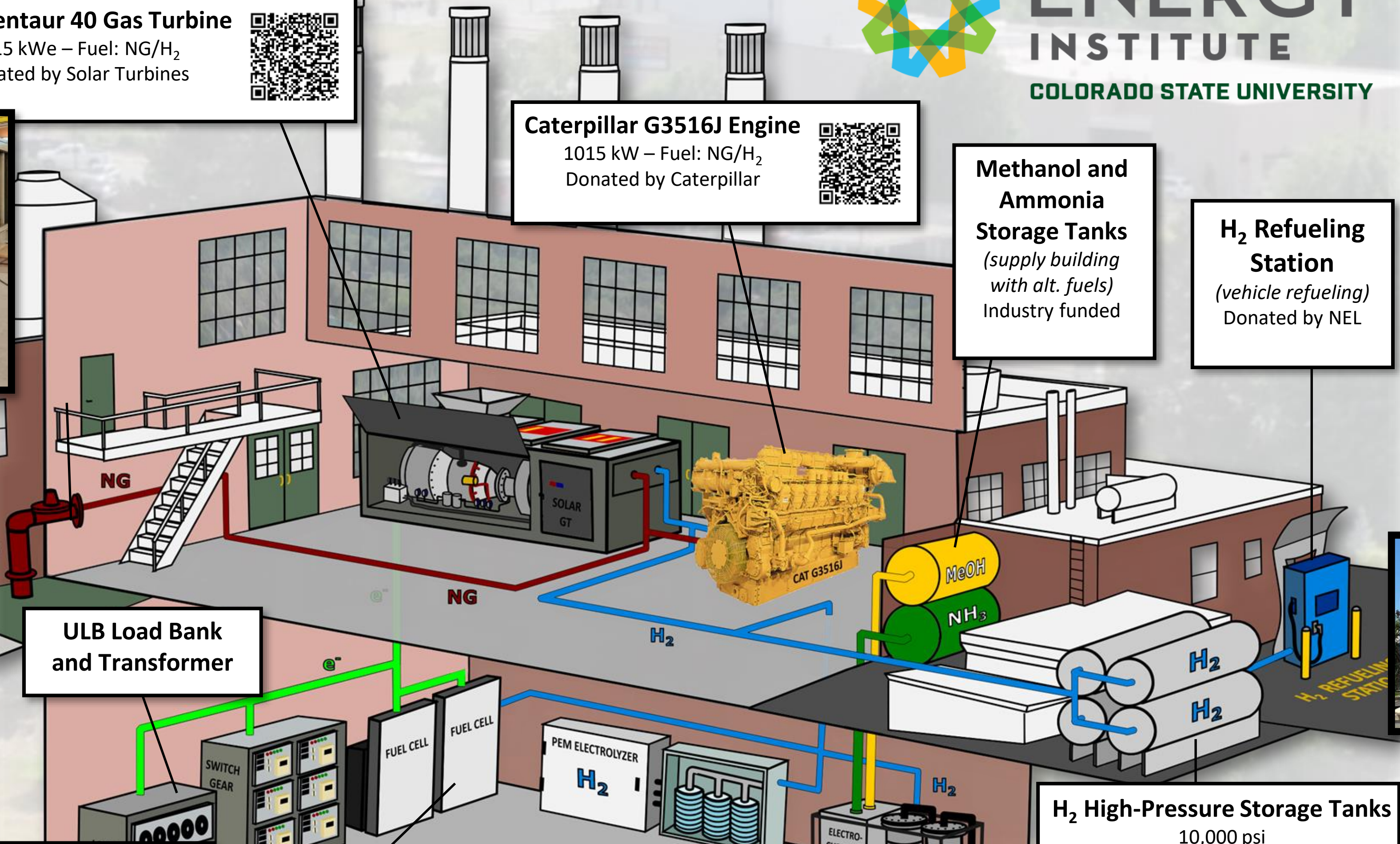
WELCOME

Launch Meeting
24 February 2023

nps.edu/decarb

Powerhouse Energy Campus: Large-scale Demonstration Research

ENERGY INSTITUTE
COLORADO STATE UNIVERSITY



Solar Centaur 40 Gas Turbine
3515 kWe – Fuel: NG/H_2
Donated by Solar Turbines

Caterpillar G3516J Engine
1015 kW – Fuel: NG/H_2
Donated by Caterpillar

Methanol and Ammonia Storage Tanks
(supply building with alt. fuels)
Industry funded

H_2 Refueling Station
(vehicle refueling)
Donated by NEL

ULB Load Bank and Transformer

H_2 High-Pressure Storage Tanks
10,000 psi

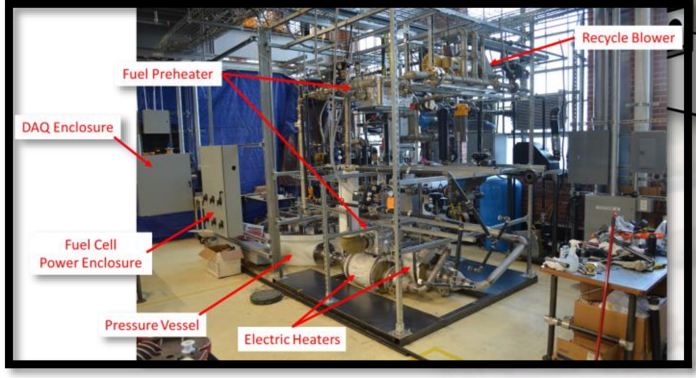
H_2 Fuel Cell Bank
(experimental units to optimize renewable energy utilization)
Industry Funded

NEL C20 PEM Electrolyzer Bank
(H_2 generation); 30 Nm³/h of H_2
Donated by NEL

Electrochemical Fuel Synthesis
(production of methanol and ammonia through carbon-neutral means)
Industry funded

3.5 MWe Centaur 40 GT (Solar Turbines)

300 kWth heat activated cooling system (TCCS)



100 kWe Hybrid SOFC-Engine Powerplant (η~70%)

1 MWe CAT 3516

Large Scale Engine Testing with Hydrogen

120 kWe PEM electrolysis/ refueling (40 kg/day)

Micro Ammonia Production System

Bret Windom – bret.windom@colostate.edu
Todd Bandhauer – todd.bandhauer@colostate.edu

THE GEORGE
WASHINGTON
UNIVERSITY

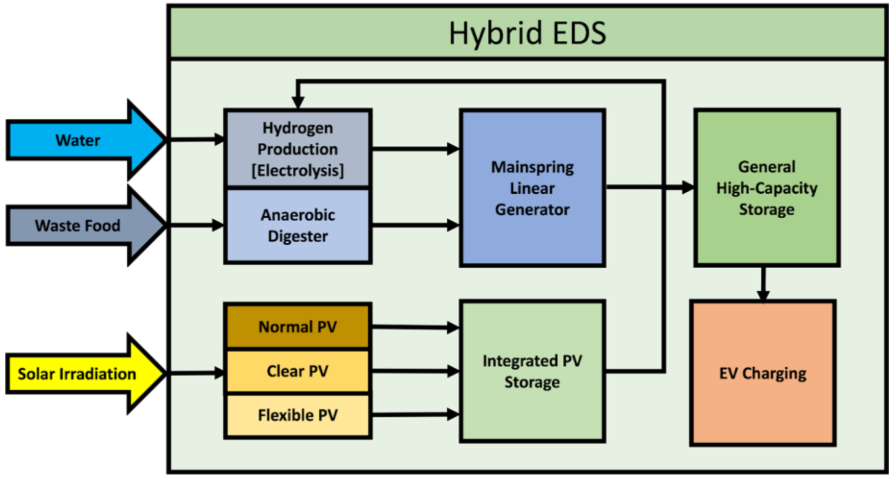
WASHINGTON, DC

Advancing Decarbonization via

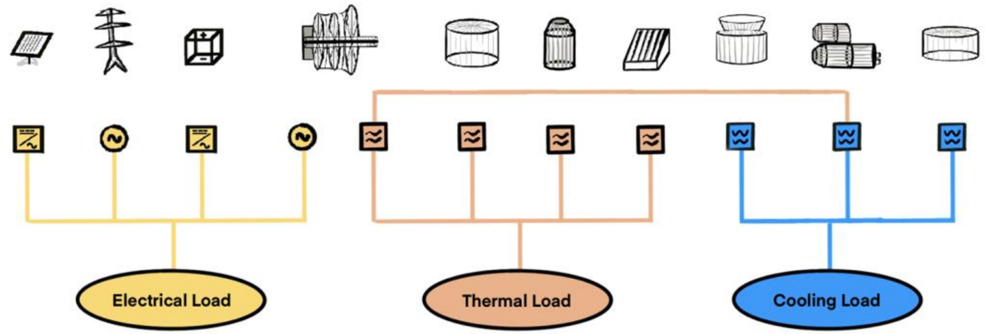
Technology R&D *Organizational Transition & Policy*

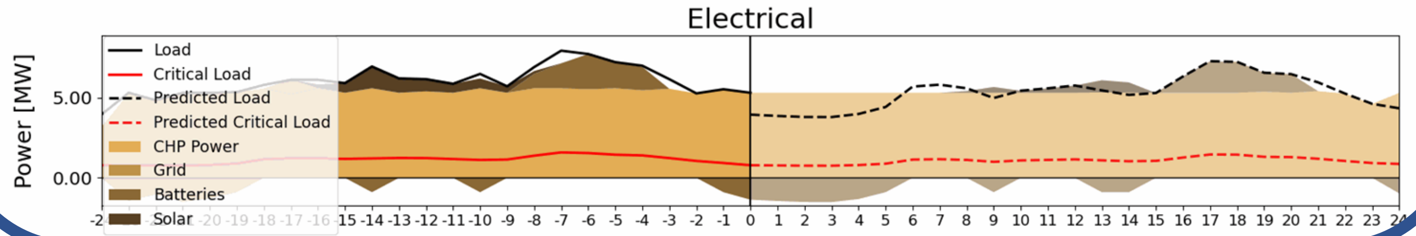
Training & Logistics *Convening*

Technology Demonstration Site



Energy Modeling & Management Systems





DOD Advising

- **DOD UARCs:** Systems Engineering Research Center, Acquisition Innovation Research Center
- **Project for Media & National Security:** briefings for Defense Writers Group to connect senior policy makers that link national security to climate action

Grainger College
of Engineering
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Decarbonization Research Consortium
Office Naval Research
Naval Postgraduate School

February 2023

- **Clean hydrogen technologies (Perry, Kenis, Gewirth, Sofronis, Miljkovic, Elbel)**
  - Protonic Ceramic Fuel/Electrolysis Cells for Green H2 or other commodities
    - Catalysts for steam splitting
    - More stable materials & interfaces, understanding of degradation mechanisms and rational mitigation of degradation built into materials/devices
    - High temperature response of metallic materials in hydrogen is unexplored
    - Thermomechanical stresses and degradation
  - Hydrogen transport using ammonia as the carrier, recovering H_2 from ammonia via electrolysis
    - Durability, efficiency, interaction with metallic surfaces
  - Thermal management of H_2 platforms
    - PEM fuel cells operate at lower temperature; maintaining safe operating temperature and good power density is difficult because it requires heat rejection at low temperature differences
  - Alkaline Electrolyzers
    - Hydrodynamics and surface/interface of bubble removal, current density that is allowable
- **Commercially practical electrofuels (Lee, Kenis, Gewirth, Cai, Ansell)**
  - CO_2 reduction
    - Small molecule (such as glycerol and methanol) oxidation to increase energy efficiency in CO_2 reduction
    - durability, selectivity, efficiency
  - Direct conversion of methane to higher value fuels
- **Industrial heat and efficiency of industrial processes (Kenis, Miljkovic, Elbel)**
  - High temperature heat pump
    - Efficient working fluids (refrigerants, durability of compressors and valves, lubricants, etc.)
  - High Power Density Thermal Systems
    - Ship thermal management systems need to be power dense and handle transient heat loads
  - Heat transfer in two-phase processes
    - Durable materials and coatings required - for example in dropwise condensation or high quality flow boiling

- **Circular economy, wastewater treatment (Cai, Su)**
  - Manufacture of low cost nanocrystalline diamonds (NCDs) for wastewater treatment, electrochemical conversion
    - Current state-of-the-art approaches to fabricating nanoscale diamonds rely on high-pressure or low-pressure processes and lack scalability and controllability (flame synthesis)
- **Fourth generation low-GWP synthetic refrigerants (Miljkovic, Elbel)**
  - Toxicity (ammonia), pressure (CO2), flammability (butane, pentane)
- **Technologies for buildings (Miljkovic, Cai, Elbel)**
  - Thermochemical energy storage and phase change materials are important to enable electrification
  - Affordable, intelligent, energy-efficient, and environmentally benign thermoregulation materials in building thermal management
- **Sustainable energy carriers for aviation (Lee, Kenis, Gewirth, Cai, Ansell)**
  - Challenges to scalability, resource, cost, and integration moving from conventional kereosene-based aviation fuels to alternatives
  - Evaluating socio-techno-economic factors of alternate fuels for aircraft.
  - Includes commercial practicality of electrofuels and other low carbon fuels
- **Electric grid stability (Gross, Kontou)**
  - The V2X concept of the integration of EVs – electric vehicles – into the grid
  - Integration of renewables (PV and Wind) with today’s grid: opportunity for electrical energy storage
  - Managing multi-modal electrified transportation systems with renewables and integrated with batteries for grid stability

NEIT

Nanoscale Energy and Interfacial Transport

Our Mission:

Thermal management of high powered micro- and power electronics and development of novel materials for thermal energy storage and dissipation.

Research Interests:

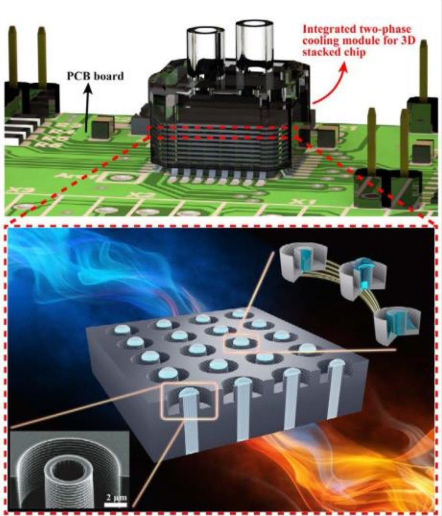
- Surface engineering at micro- and nano-length scale for 2-phase thermal enhancement
- Nanomaterials for thermal transport and energy storage
- Phase change heat transfer for pulsating electronic loads
- Electronics packaging and microfabrication

Damena Agonafer
Associate Professor, Clark Faculty Fellow, UMD
Center for Advanced Lifecycle Engineering (CALCE)
agonafer@umd.edu

In the Media

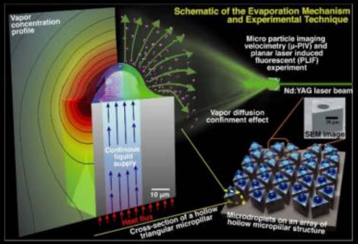
The Electronics Cooling System 400 Million Years in the Making : How an ancient insect can help ensure progress in electronics

PUTTING A MENISCUS ON MICROPILLARS COOLS ELECTRONICS

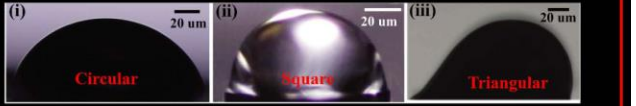


Fundamental Research

Evaporative Heat Transfer from Asymmetric Microdroplets confined on micropillars



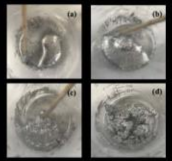
Micro Engineered Surfaces for Droplet Shape Manipulation for enhanced Evaporative Transfer



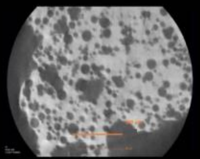
Micro Engineered Surfaces for Bubble Shape Manipulation for enhanced Immersion Boiling

Composite Phase Change Materials for SWaP-C and Performace Optimization for transient electronic loads

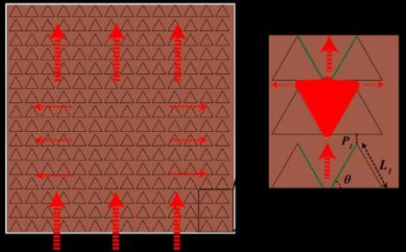
PCM Synthesis

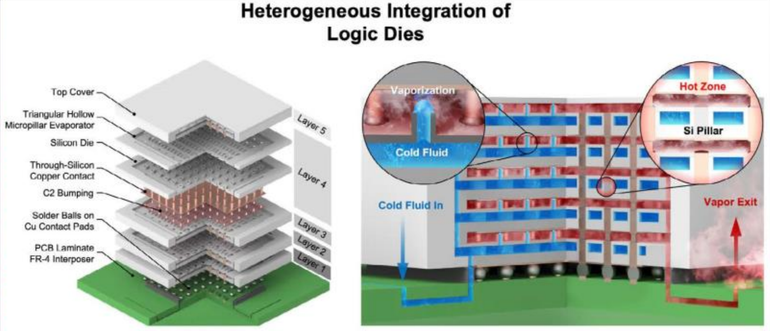


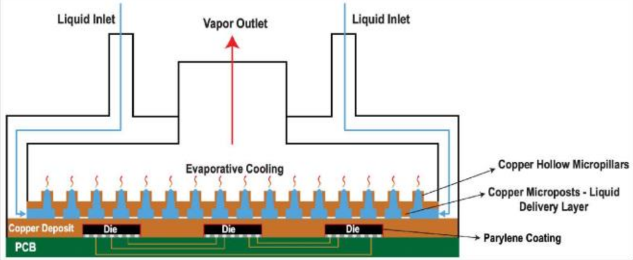
PCM Characterization



Novel Capillary Wick Design for Enhanced Capillary Limit for Vapor Chambers







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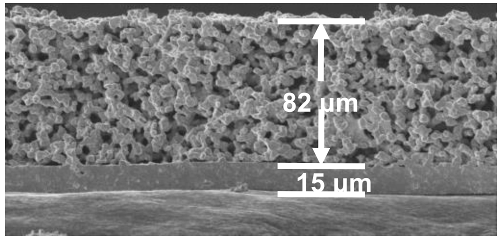
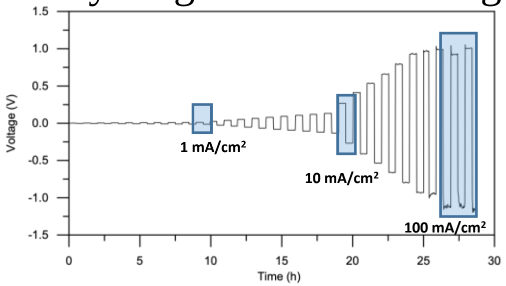
UNIVERSITY OF MARYLAND 1856

A. JAMES CLARK SCHOOL OF ENGINEERING

Safe, High-Energy-Density & High-Rate-Capable, Solid-State Batteries

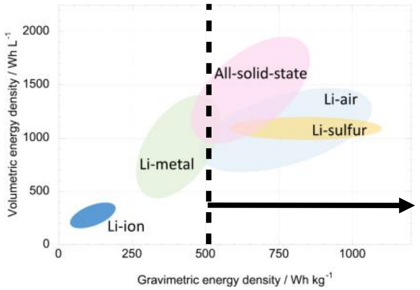
- Developed advanced 3D ceramic architectures and surface modification that enables Li_{metal} cycling rates 10X DOE goal





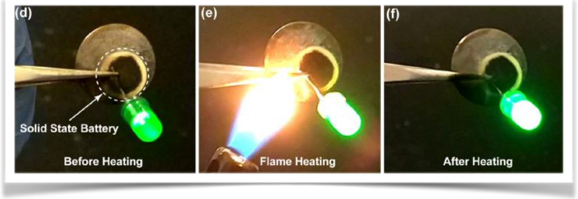
- A potential step change in energy density that enables flight applications

Solid-state enables Li-metal anodes and advanced cathodes for potential step change in cell energy density

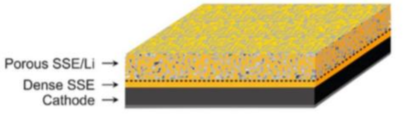


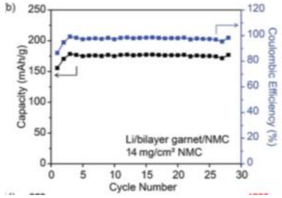
- Moreover, these solid-state batteries are non-flammable and offer a much wider operating temperature range

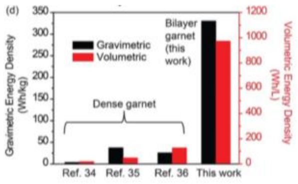
Wider operating temperature range negates thermal management (cooling) requirements, further increasing pack/system energy density, and enabling
close coupling with heat sources, from local power for critical circuits to hybrid propulsion systems

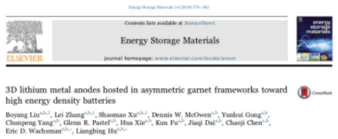


- This architecture is cathode agnostic from high-energy density Li-NMC to Li-S and Li-air batteries








Energy Storage Materials 14 (2018) 376–382

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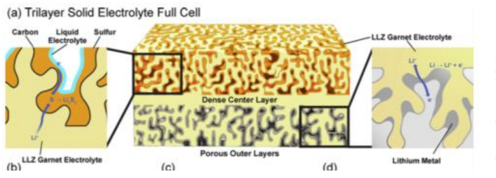
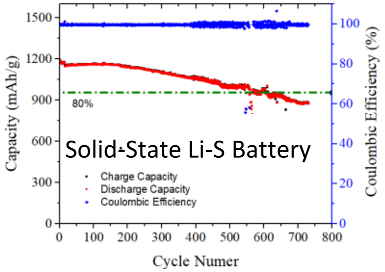
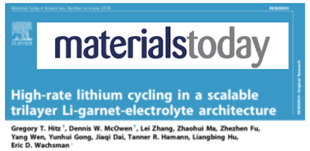
journal homepage: www.elsevier.com/locate/ensm

3D lithium metal anodes hosted in asymmetric garnet frameworks toward high energy density batteries

Boyang Liu[a,b,1], Lei Zhang[a,b,1], Shaomao Xu[a,b,1], Dennis W. McOwen[a,b], Yunhui Gong[a,b], Chunpeng Yang[a,b], Glenn R. Pastel[a,b], Hua Xie[a,b], Kun Fu[a,b], Jiaqi Dai[a,b], Chaoji Chen[a,b], Eric D. Wachsman[a,b,*], Liangbing Hu[a,b,*]





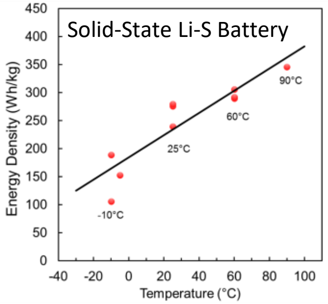

Materials Today • Volume xxx, Number xx • xxxx 2018

RESEARCH

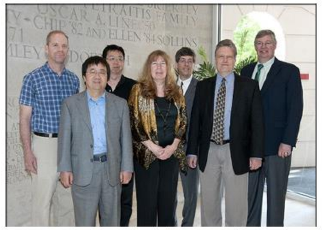
materialstoday

High-rate lithium cycling in a scalable trilayer Li-garnet-electrolyte architecture

Gregory T. Hitz[†], Dennis W. McOwen[†], Lei Zhang, Zhaohui Ma, Zhezhen Fu, Yang Wen, Yunhui Gong, Jiaqi Dai, Tanner R. Hamann, Liangbing Hu, Eric D. Wachsman[*]



CENTER FOR RESEARCH ON EXTREME BATTERIES



CREB Steering Committee:
UMD: Chunsheng Wang (*UMD CREB Director*) & Eric Wachsman
ARL: Wesley Henderson (*ARL CREB Lead*) & Kang Xu
NIST: Joseph Dura & David Jacobson
NYBEST: William Acker
BNL/Stony Brook U: Esther Takeuchi - *Presidential Medal Technology*
ANL: Kahlil Amine
SUNY: Stan Whittingham - *Nobel Laureate*

***Honorary Life Member and ARL CREB Founder:** Cynthia Lundgren

Program Administrator: James Short

Universities

National Labs

Industry

MARYLAND ENERGY INNOVATION INSTITUTE

\- Prof. Eric Wachsman

Next Generation Solid Oxide Fuel Cells

Lowering the Temperature of Solid Oxide Fuel Cells
Eric D. Wachsman, *et al.*
Science **334**, 935 (2011);
DOI: 10.1126/science.1204090

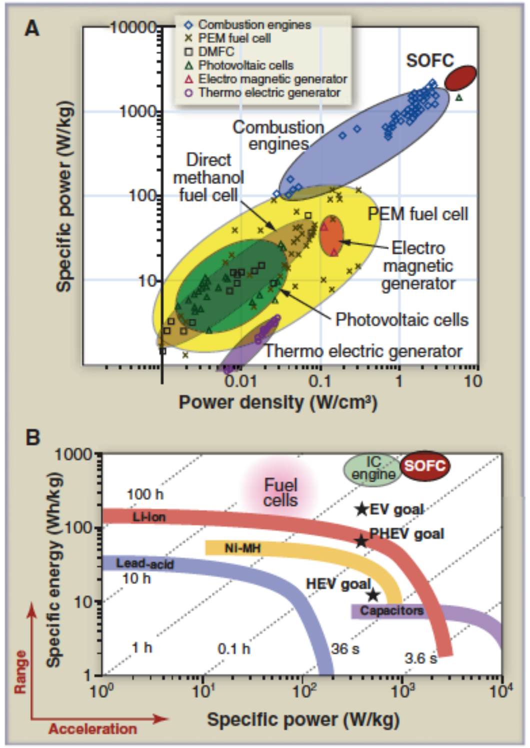
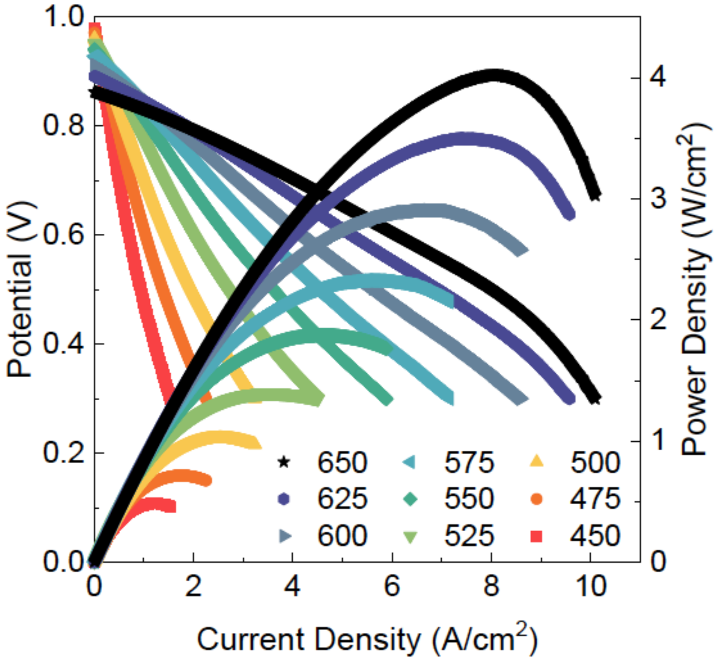
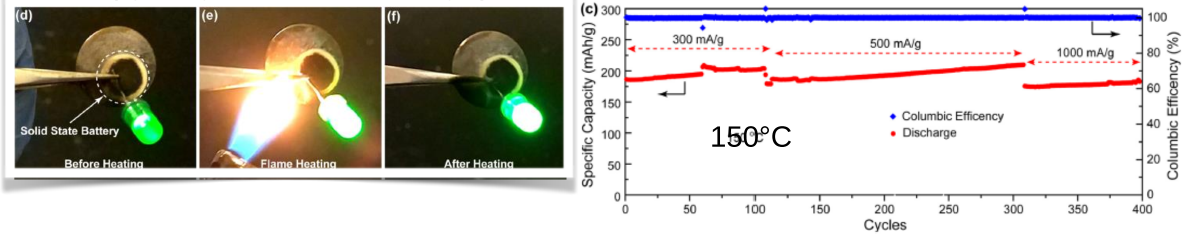


Fig. 4. (**A**) Comparison of specific power of the present ~2W/cm^2 SOFC at 650°C compared with various energy conversion devices as a function of power density (*23*). (**B**) Ragone plot (specific energy versus specific power) for various energy devices (*40*) compared with the present SOFC.

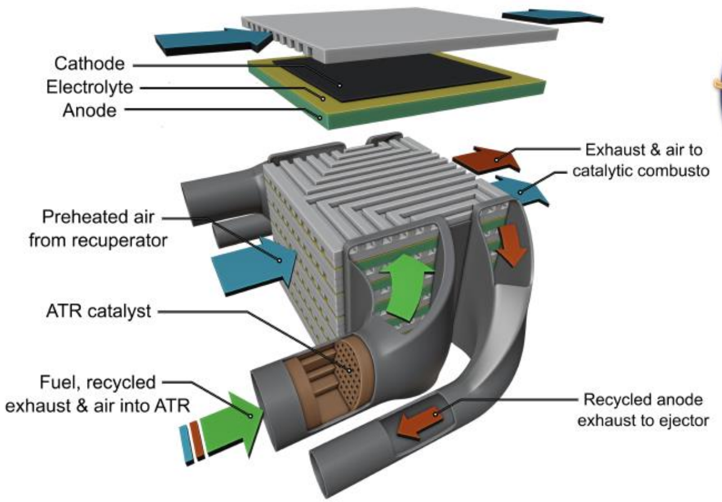
- ~2X Fuel efficiency of IC engines
- Have since doubled the power density to ~4 W/cm^2 at 650°C



- The safety and high operating temperature capability of our solid-state batteries enables thermal and electrical integration with our lower temperature SOFCs for high energy & power density generation/storage hybrid systems



- Currently integrating SOFCs into gas turbine for higher efficiency and power under ARPA-E REEACH program for electrification of flight



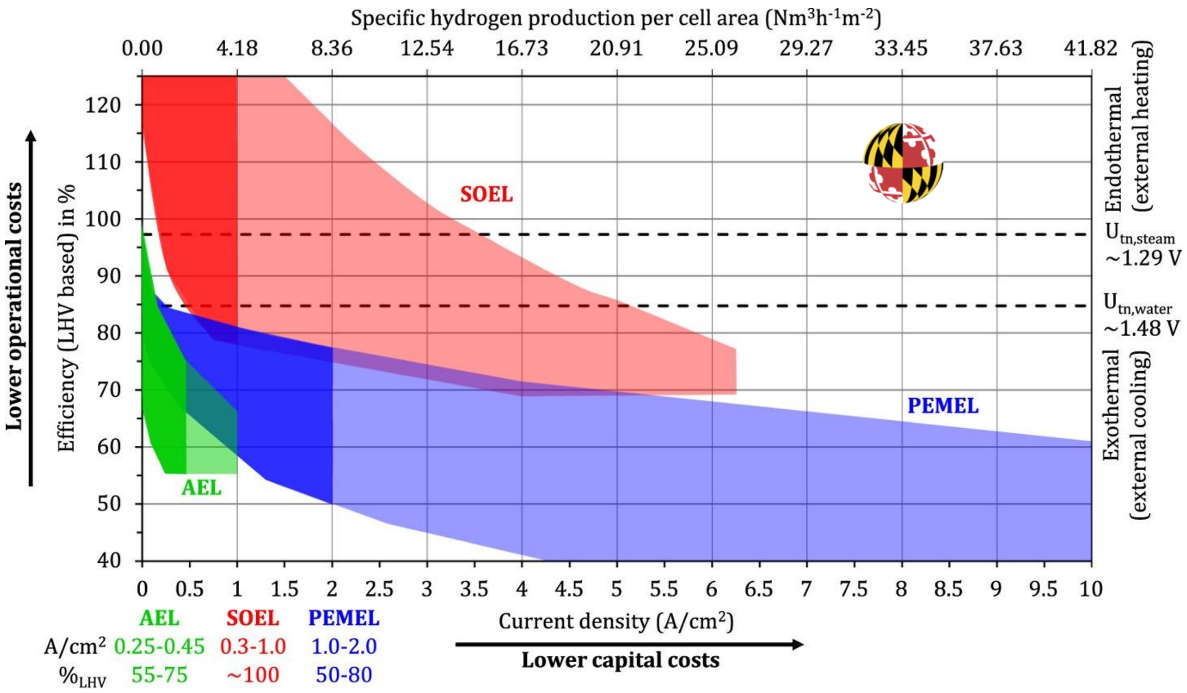
- Became the **benchmark for multiple US DOD solicitations,** e.g.,:

Ultra-High Power Density Solid Oxide Fuel Cell Stack for High Efficiency Propulsion and Power Systems
DoD OSD SBIR 2013.3 - Topic OSD13-EP4

TECHNOLOGY AREAS: Ground/Sea Vehicles, Materials/Processes

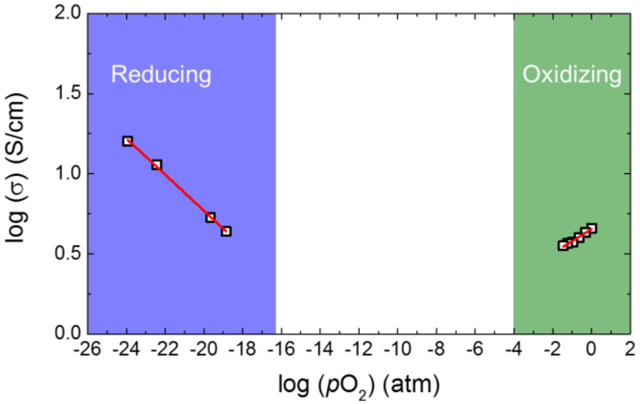
MARYLAND ENERGY INNOVATION INSTITUTE - Prof. Eric Wachsman

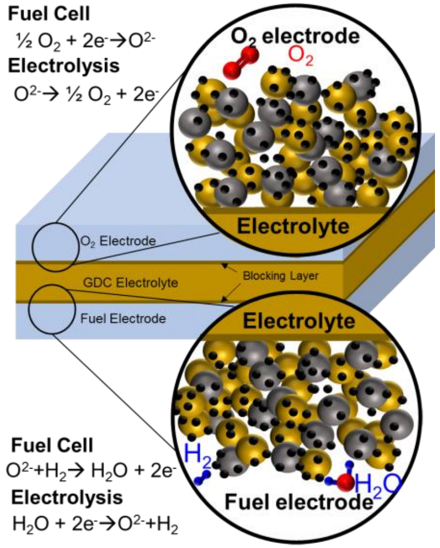
Solid Oxide Electrolysis Cells for Lower Cost H_2 Production and Long Term Energy Storage



	AEL	SOEL	PEMEL
A/cm²	0.25-0.45	0.3-1.0	1.0-2.0
$\%_{LHV}$	55-75	~100	50-80

- In addition we have developed ceramic electrode materials that are stable in both oxidizing and reducing conditions enabling an integrated SOFC/SOEL unit for long term energy storage in a single unitized device





Fuel Cell
$\frac{1}{2} O_2 + 2e^- \rightarrow O^{2-}$
Electrolysis
$O^{2-} \rightarrow \frac{1}{2} O_2 + 2e^-$

Fuel Cell
$O^{2-} + H_2 \rightarrow H_2O + 2e^-$
Electrolysis
$H_2O + 2e^- \rightarrow O^{2-} + H_2$

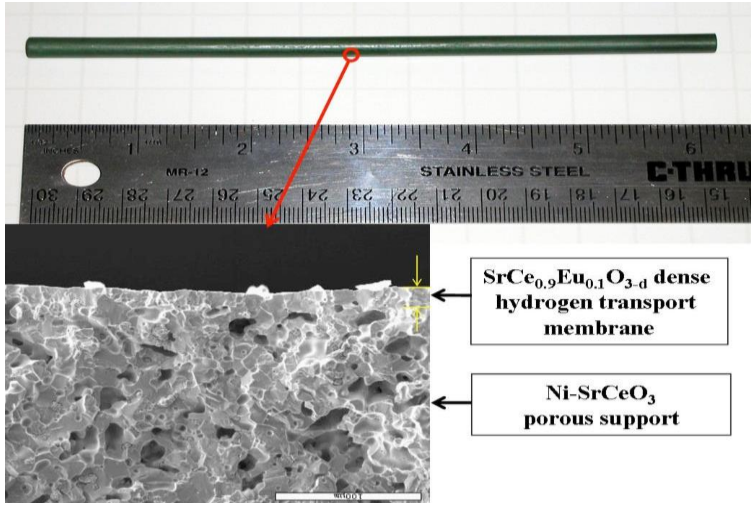
- Solid Oxide Electrolysis Cells have ~2X efficiency of current PEM based cells, a potential ~2X decrease in OPEX
- However, current solid oxide cells have lower current density increasing CAPEX
- Our next generation Solid Oxide Electrolysis Cells match the current density of PEM cells thus potential ~2X reduction in OPEX at similar CAPEX

MARYLAND ENERGY
INNOVATION INSTITUTE

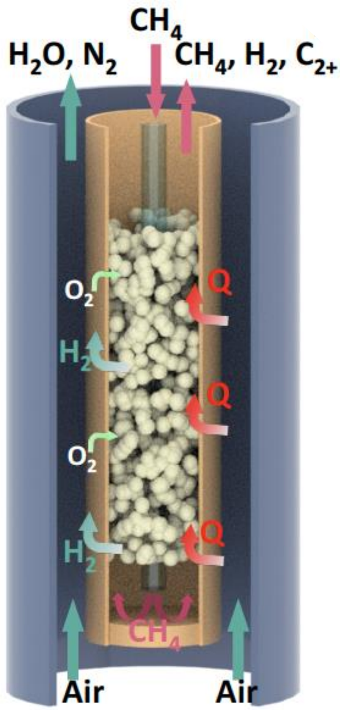
- Prof. Eric Wachsman

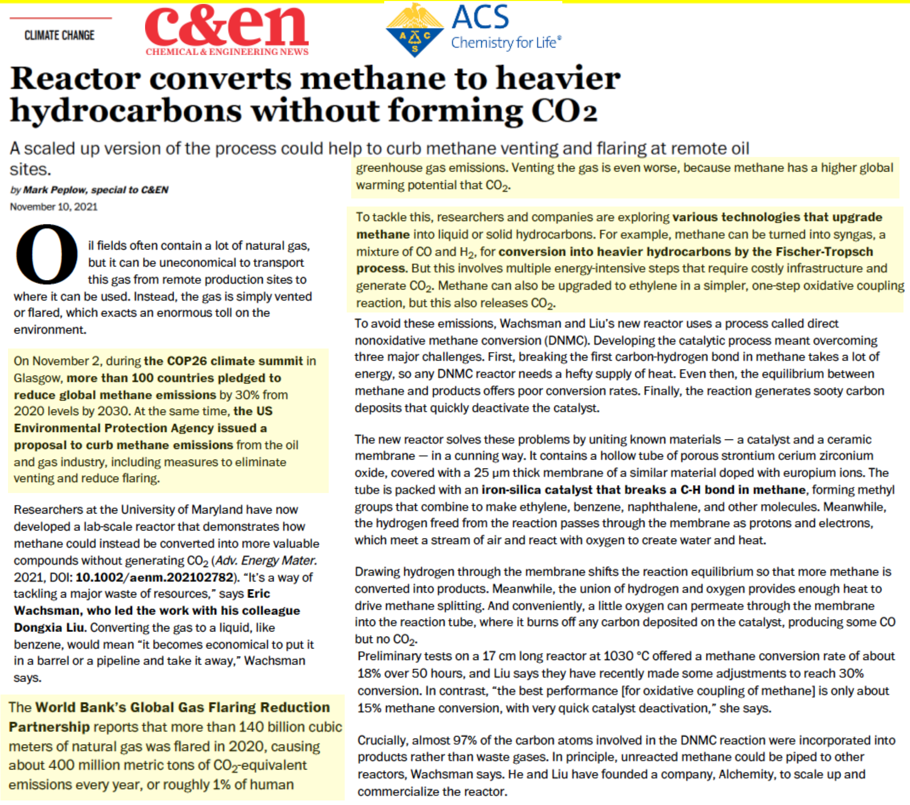
H_2 and Logistics Fuel Production with Negligible GHG Emissions

- Integrated catalytic membrane reactor produces pure H_2 by permeation through mixed protonic/electronic conducting dense ceramic membrane



- Platform technology for numerous chemical reactions





Reactor converts methane to heavier hydrocarbons without forming CO2

A scaled up version of the process could help to curb methane venting and flaring at remote oil sites.

by ***Mark Peplow, special to C&EN***

November 10, 2021

Oil fields often contain a lot of natural gas, but it can be uneconomical to transport this gas from remote production sites to where it can be used. Instead, the gas is simply vented or flared, which exacts an enormous toll on the environment.

On November 2, during **the COP26 climate summit** in Glasgow, **more than 100 countries pledged to reduce global methane emissions** by 30% from 2020 levels by 2030. At the same time, **the US Environmental Protection Agency issued a proposal to curb methane emissions** from the oil and gas industry, including measures to eliminate venting and reduce flaring.

Researchers at the University of Maryland have now developed a lab-scale reactor that demonstrates how methane could instead be converted into more valuable compounds without generating CO_2 (*Adv. Energy Mater.* 2021, DOI: **10.1002/aenm.202102782**). "It's a way of tackling a major waste of resources," says **Eric Wachsman, who led the work with his colleague Dongxia Liu.** Converting the gas to a liquid, like benzene, would mean "it becomes economical to put it in a barrel or a pipeline and take it away," Wachsman says.

The **World Bank's Global Gas Flaring Reduction Partnership** reports that more than 140 billion cubic meters of natural gas was flared in 2020, causing about 400 million metric tons of CO_2-equivalent emissions every year, or roughly 1% of human greenhouse gas emissions. Venting the gas is even worse, because methane has a higher global warming potential that CO_2.

To tackle this, researchers and companies are exploring **various technologies that upgrade methane** into liquid or solid hydrocarbons. For example, methane can be turned into syngas, a mixture of CO and H_2, for **conversion into heavier hydrocarbons by the Fischer-Tropsch process.** But this involves multiple energy-intensive steps that require costly infrastructure and generate CO_2. Methane can also be upgraded to ethylene in a simpler, one-step oxidative coupling reaction, but this also releases CO_2.

To avoid these emissions, Wachsman and Liu's new reactor uses a process called direct nonoxidative methane conversion (DNMC). Developing the catalytic process meant overcoming three major challenges. First, breaking the first carbon-hydrogen bond in methane takes a lot of energy, so any DNMC reactor needs a hefty supply of heat. Even then, the equilibrium between methane and products offers poor conversion rates. Finally, the reaction generates sooty carbon deposits that quickly deactivate the catalyst.

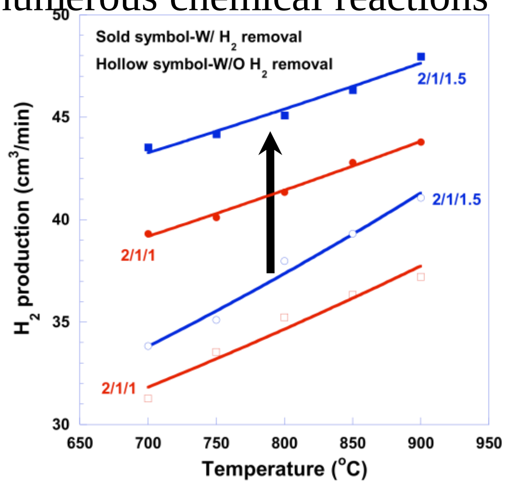
The new reactor solves these problems by uniting known materials — a catalyst and a ceramic membrane — in a cunning way. It contains a hollow tube of porous strontium cerium zirconium oxide, covered with a 25 µm thick membrane of a similar material doped with europium ions. The tube is packed with an **iron-silica catalyst that breaks a C-H bond in methane**, forming methyl groups that combine to make ethylene, benzene, naphthalene, and other molecules. Meanwhile, the hydrogen freed from the reaction passes through the membrane as protons and electrons, which meet a stream of air and react with oxygen to create water and heat.

Drawing hydrogen through the membrane shifts the reaction equilibrium so that more methane is converted into products. Meanwhile, the union of hydrogen and oxygen provides enough heat to drive methane splitting. And conveniently, a little oxygen can permeate through the membrane into the reaction tube, where it burns off any carbon deposited on the catalyst, producing some CO but no CO_2.

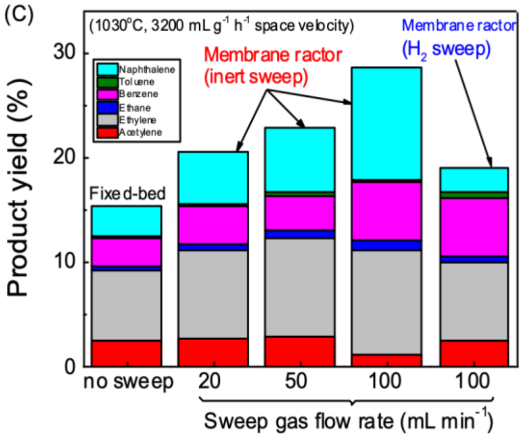
Preliminary tests on a 17 cm long reactor at 1030 °C offered a methane conversion rate of about 18% over 50 hours, and Liu says they have recently made some adjustments to reach 30% conversion. In contrast, "the best performance [for oxidative coupling of methane] is only about 15% methane conversion, with very quick catalyst deactivation," she says.

Crucially, almost 97% of the carbon atoms involved in the DNMC reaction were incorporated into products rather than waste gases. In principle, unreacted methane could be piped to other reactors, Wachsman says. He and Liu have founded a company, Alchemity, to scale up and commercialize the reactor.

- Dramatically lower GHG emission and cost than conventional SRM H_2 production



- Co-produce C_{2+} (e.g., ethylene, benzene) and pure H_2 with high single step yields



- **Only GTL technology with no GHG emissions**

MARYLAND ENERGY INNOVATION INSTITUTE

\- Prof. Eric Wachsman

Trade space exploration for climate impact and quality attributes for navy ships

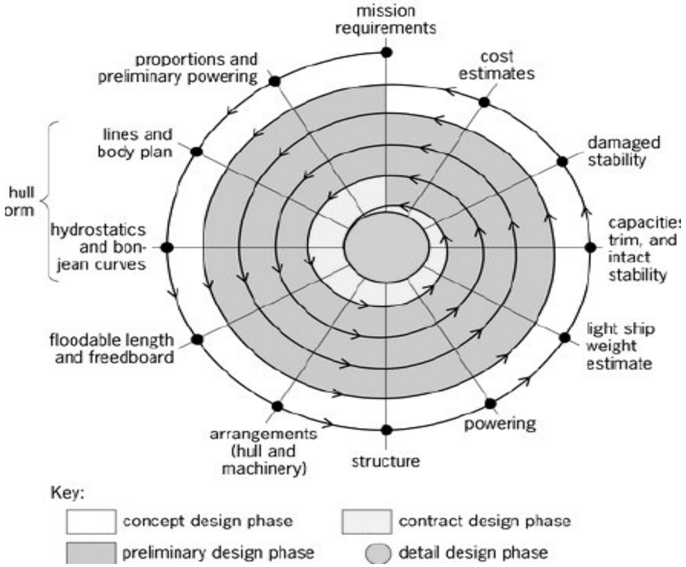
Ronald E. Giachetti, PhD
Professor and Chair
Department of Systems Engineering
Naval Postgraduate School
regiache@nps.edu

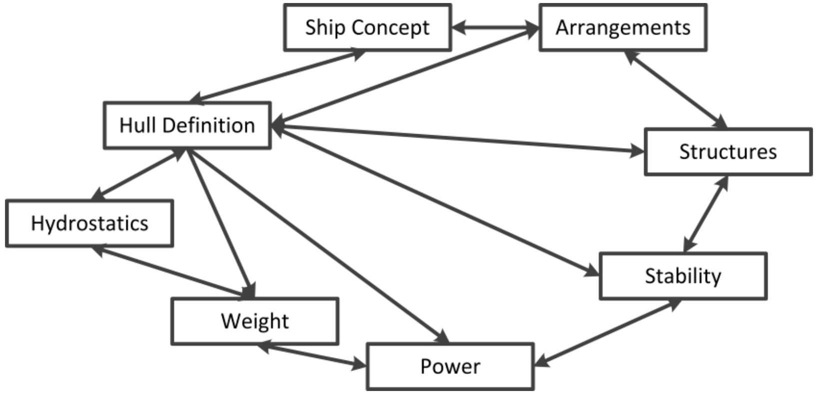
Giovanna Oriti, ECE
Douglas Van Bossuyt, SE
Daniel Reich, OR

February 28, 2023

Navy Ship Design

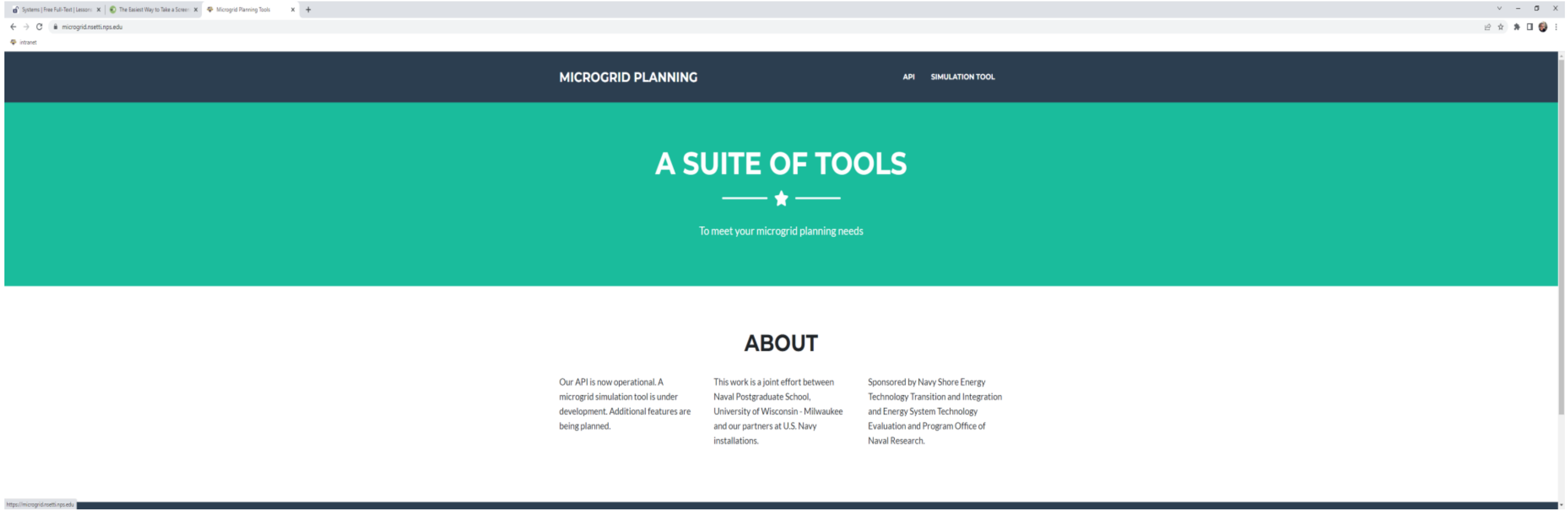
- Iterative and incremental method
- Early design decisions lock in ~ 70% of cost
- Many different objectives, many interdependencies between concerns
- Minimization of GHG emissions becomes one of many design objectives





Trade space exploration

- Incorporate measures of GHG emissions into the conceptual design phase for ships
- Our focus is on the engineering design tools



MICROGRID PLANNING

A SUITE OF TOOLS

To meet your microgrid planning needs

ABOUT

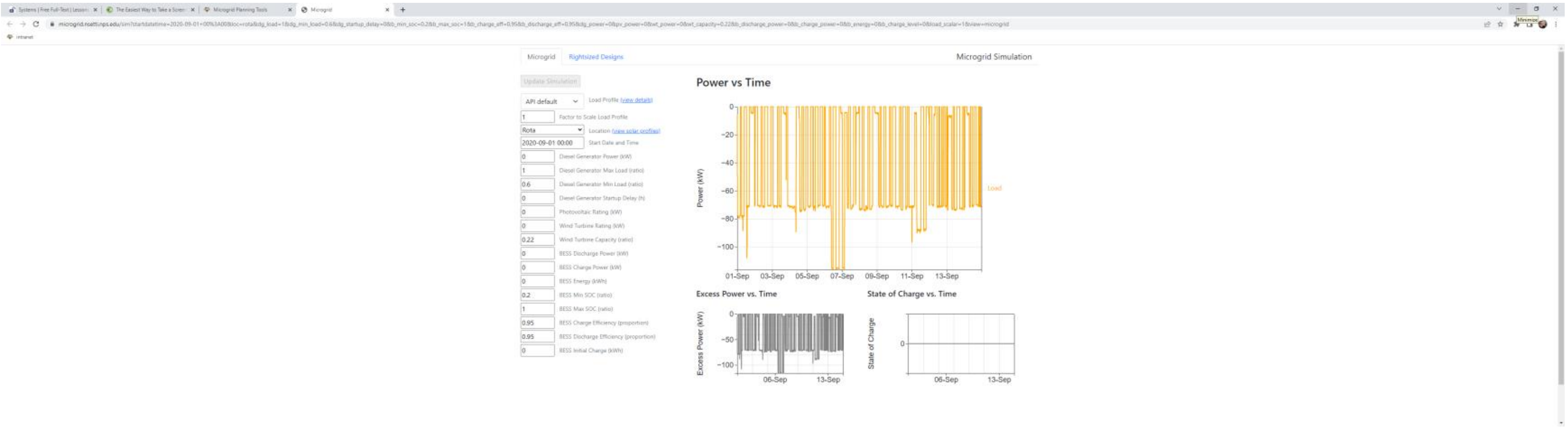
Our API is now operational. A microgrid simulation tool is under development. Additional features are being planned.

This work is a joint effort between Naval Postgraduate School, University of Wisconsin - Milwaukee and our partners at U.S. Navy installations.

Sponsored by Navy Shore Energy Technology Transition and Integration and Energy System Technology Evaluation and Program Office of Naval Research.

https://microgrid.nsetti.nps.edu/

Design Tool



microgrid.nsetti.nps.edu/sim?startdatetime=2020-09-01+00%3A00&loc=rota&dg_load=1&dg_min_load=0.6&dg_startup_delay=0&b_min_soc=0.2&b_max_soc=1&b_charge_eff=0.95&b_discharge_eff=0.95&dg_power=0&pv_power=0&wt_power=0&wt_capacity=0.22&b_discharge_power=0&b_charge_power=0&b_energy=0&b_charge_level=0&load_scalar=1&view=microgrid

API default	Load Profile (view details)
1	Factor to Scale Load Profile
Rota	Location (view solar profiles)
2020-09-01 00:00	Start Date and Time
0	Diesel Generator Power (kW)
1	Diesel Generator Max Load (ratio)
0.6	Diesel Generator Min Load (ratio)
0	Diesel Generator Startup Delay (h)
0	Photovoltaic Rating (kW)
0	Wind Turbine Rating (kW)
0.22	Wind Turbine Capacity (ratio)
0	BESS Discharge Power (kW)
0	BESS Charge Power (kW)
0	BESS Energy (kWh)
0.2	BESS Min SOC (ratio)
1	BESS Max SOC (ratio)
0.95	BESS Charge Efficiency (proportion)
0.95	BESS Discharge Efficiency (proportion)
0	BESS Initial Charge (kWh)

Energy Efficiency Design Index (EEDI)

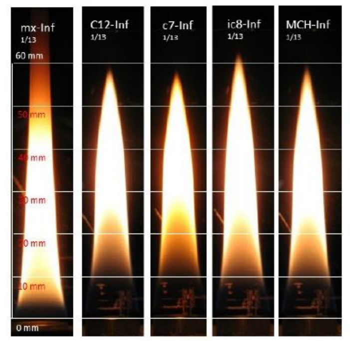
- EEDI measures the grams of carbon dioxide (CO2) per ship’s capacity mile and is calculated by a formula based on the technical design parameters for a given ship.

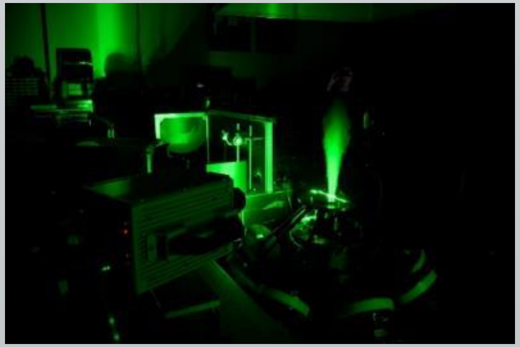
- Technical factors related to the type, cargo capacities, ship speed, hull type, main engine, turbine, propulsion, fuel, service information, dwt, etc.

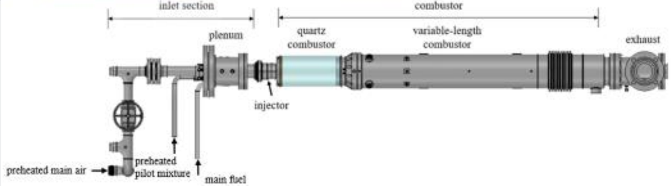
- The EEDI is for ships with the mission to transport cargo and/or people.

Jacqueline O'Connor, Associate Professor of ME, Penn State

Reacting Flow Dynamics Laboratory https://sites.psu.edu/rfdl







Fundamental studies of turbulent flames, combustor flows, fuel chemistry, and combustor emissions

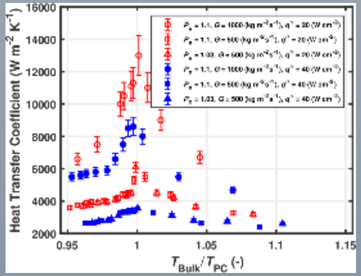
Testing of industrial hardware in acoustically-variable test facilities to understand combustor operability

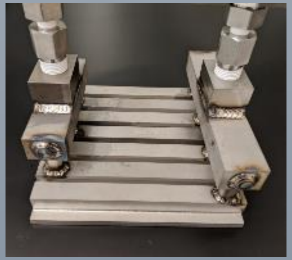
TRL: 1 2 3 4

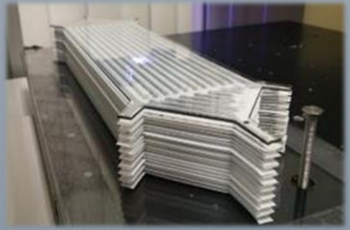
Multicomponent, multiphase, and supercritical heat and mass transfer

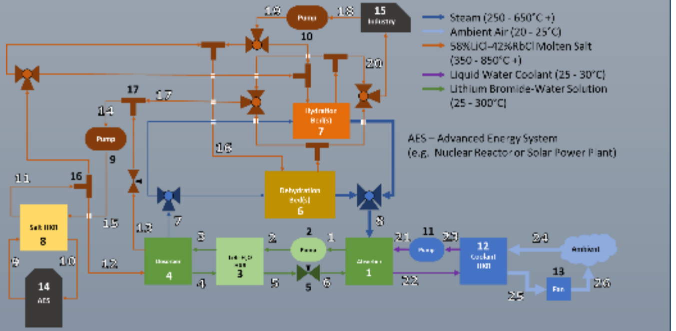
Intensified high temperature heat exchanger and reactor technology

Thermal energy system design and optimization









Brian Fronk, Associate Professor of ME, Penn State

Heat Exchange and Thermal Energy Research (HEATER) Laboratory https://sites.psu.edu/fronklab

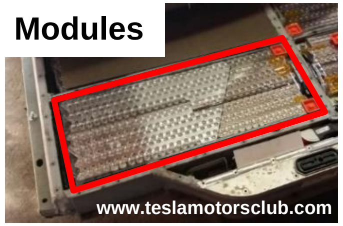
Marconnet Thermal & Energy Conversion Lab

Batteries & Electrification

Packs

www.technologyreview.com/

Modules

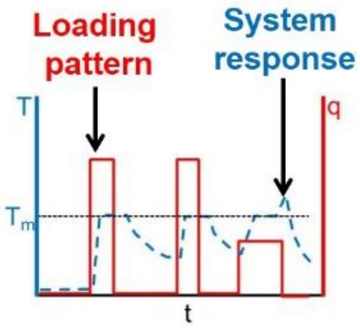


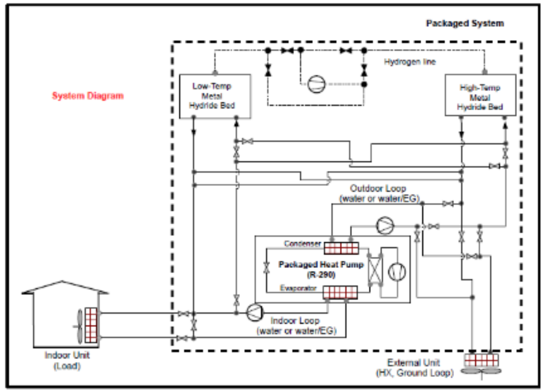
www.teslamotorsclub.com

Cells

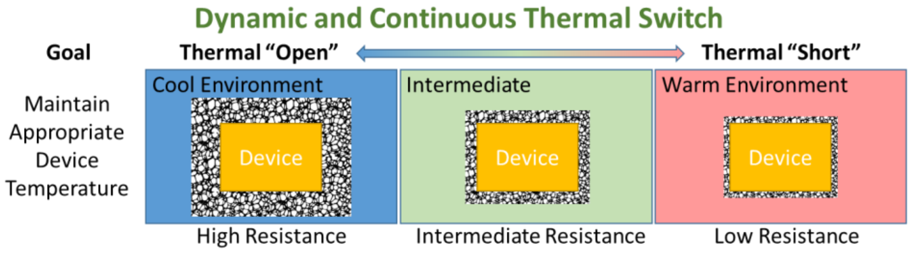
www.teslarati.com

HVAC & Energy Storage



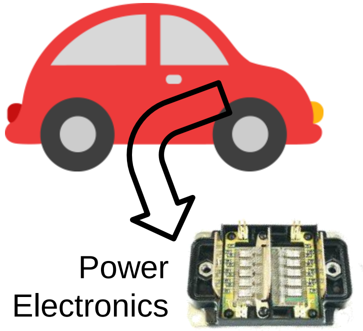


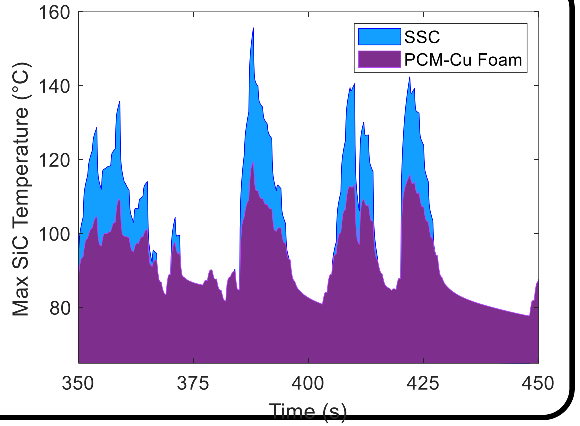
Dynamic Thermal Management



Dynamic and Continuous Thermal Switch

Goal	**Thermal “Open”** ⟷		**Thermal “Short”**
Maintain Appropriate Device Temperature	Cool Environment Device High Resistance	Intermediate Device Intermediate Resistance	Warm Environment Device Low Resistance



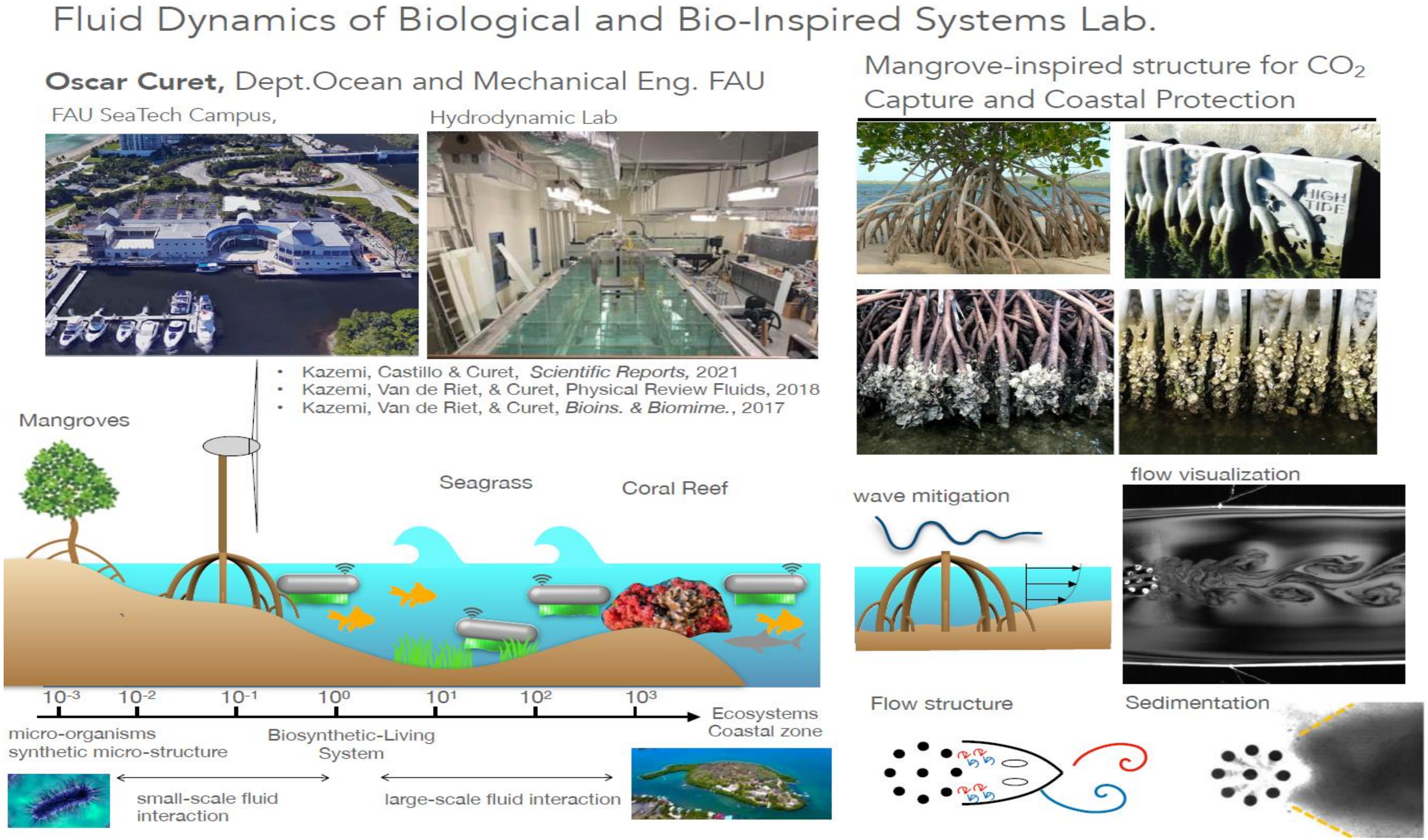


Amy Marconnet
Mechanical Engineering
marconnet@purdue.edu
engineering.purdue.edu/MTEC

Related Activities at Purdue

- Herrick Labs
  - Renewable Fuels
  - Engines & electrification
  - Center for High Performance Buildings
- Zucrow Labs
  - Combustion/Propulsion
- Institute for a Sustainable Future
  - Pursuing global resilience through climate, environment and food-energy-water security research
- Electrification & Batteries – large number of faculty involved in related research from ME, ECE, EEE, Material Science, etc.

Mangrove-inspired structure for CO2 capture and coastal protection



Fluid Dynamics of Biological and Bio-Inspired Systems Lab.

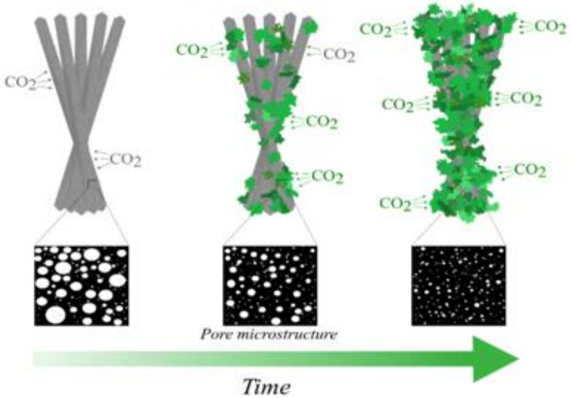
Oscar Curet, Dept.Ocean and Mechanical Eng. FAU

Mangrove-inspired structure for CO_2 Capture and Coastal Protection

- Kazemi, Castillo & Curet, *Scientific Reports,* 2021
- Kazemi, Van de Riet, & Curet, Physical Review Fluids, 2018
- Kazemi, Van de Riet, & Curet, *Bioins. & Biomime.*, 2017

Engineered-Living Structures for Coastal Protection and CO_2 Capture

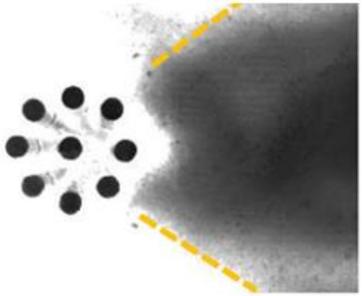
Evolution of CO_2 capturing Engineered-Living structure



1 Material-living organism interaction level

- CO_2 Capture
- Material-organism interaction

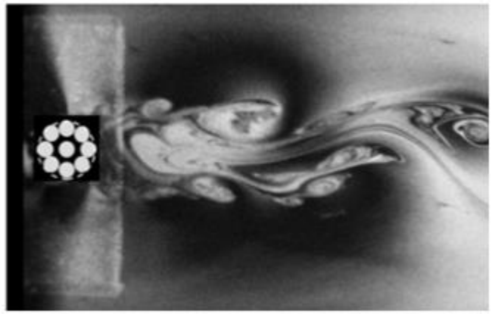
Lead: Velay-Lizancos (**Purdue**)

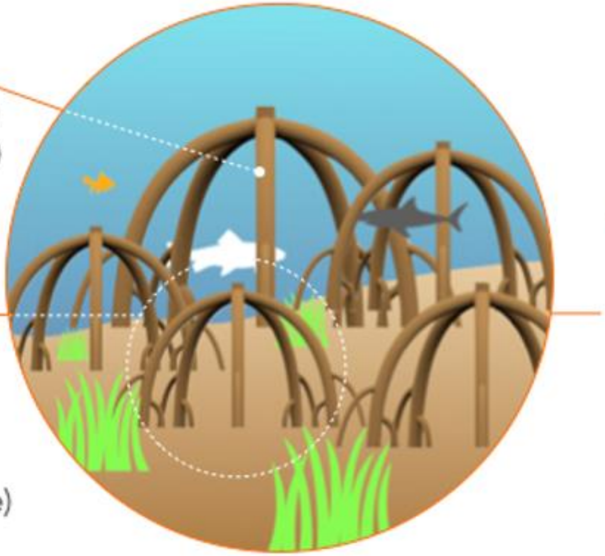


2 Structure level

- Mangrove inspired
- Fluid-structure interaction
- Erosion & wave mitigation

Leads: Curet (**FAU**), Castillo (**Purdue**)





3 Complex system level

- Engineering-living system integration
- Habitat interaction/restoration

Lead: Cruz Motta (**UPRM**)

Purdue

- Civil Eng.
- Mechanical Eng.
- Nano-materials
- Hydrodynamics
- Renewable energy

FAU*

- Ocean & Mech. Eng
- Hydrodynamics
- Biomimetics

UPRM*

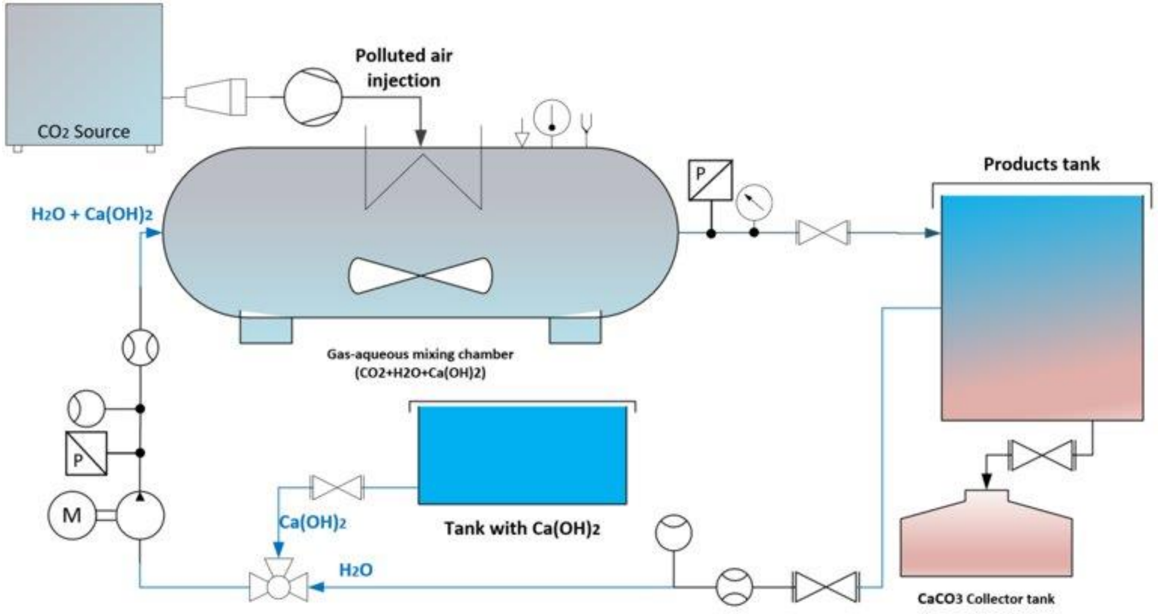
- Marine Sciences
- Coastal Facilities
- Coastal boundary layer

*Hispanic-serving Institution

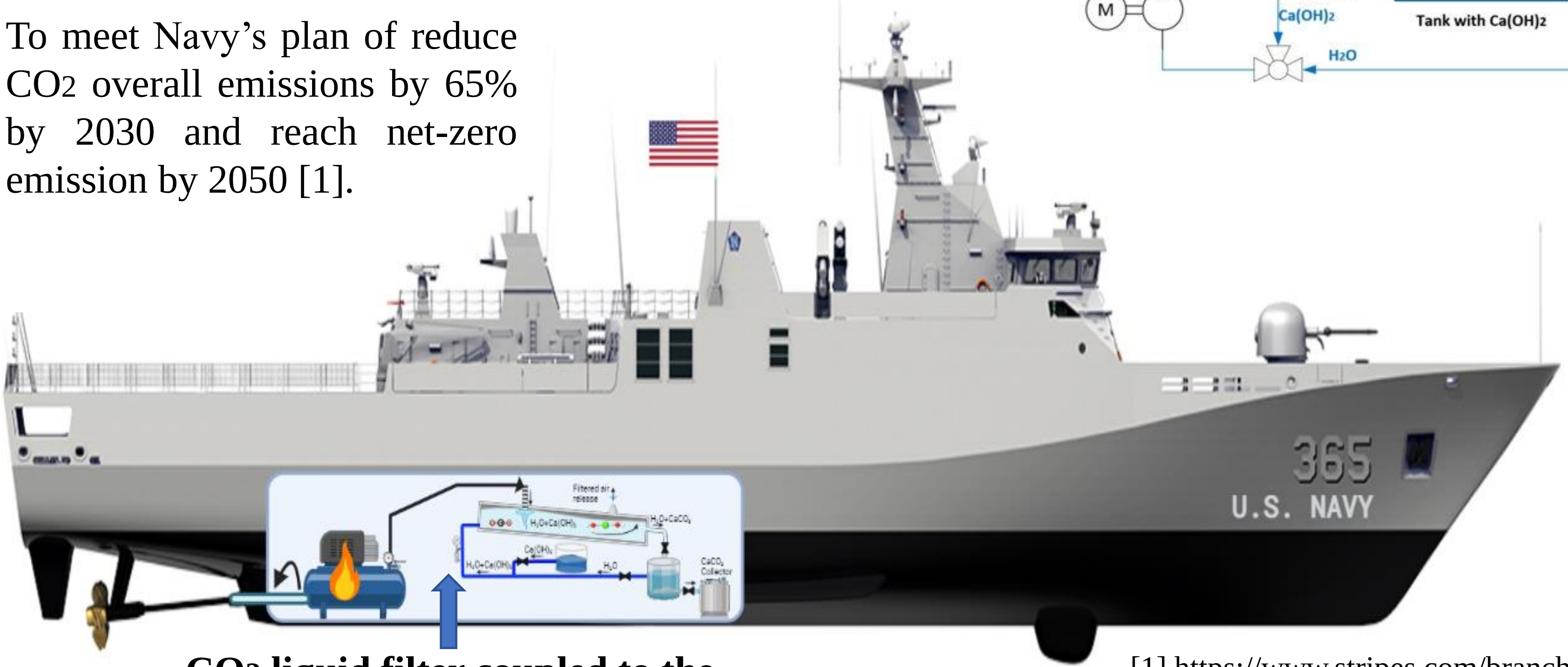
CO_2 capture liquid filter

Main concept: closed-circuit version for naval applications

Luciano Castillo & Velay-Lizancos (Purdue University)



To meet Navy’s plan of reduce CO_2 overall emissions by 65% by 2030 and reach net-zero emission by 2050 [1].



CO_2 liquid filter coupled to the ICE's exhaust of diesel-powered ships.

[1] https://www.stripes.com/branches/navy/2022-05-25/navy-climate-strategy-curb-emissions-6126159.html

Potential Projects to support ONR Energy Security efforts

Mark McVay
DOD Liaison

Ongoing Research Efforts with Potential to support reducing shipboard energy use

Alternative fuels   creation and storage

New battery storage technologies   potential for shipboard use

Shipboard energy efficiency   - follow-on to work Amory Lovins did with SSN’s

Alternative onboard power generation   Fuel Cells and Hydrogen

Conversion of CO2 and Hydrogen to Liquid fuels

Energy Efficient evaporative cooling for electronic systems

Use of Magnetic Inductors for high heat loads

Highly efficient water electrolysis for water purification and H2 production

Efficient and modular micro-grids for shipboard use

Integrative design for radical energy efficiency

Navy Decarbonization Research Consortium
24 Feb 2023 (virtual)

Amory B. Lovins
Adjunct Professor of Civil & Environmental Engineering and
Precourt Scholar, Precourt Institute for Energy
Doerr School of Sustainability
Stanford University
Professor of Practice, NPS, 2011–17
ablovins@stanford.edu
Cofounder and Chairman Emeritus, RMI (www.rmi.org)

Background at https://doi.org/10.1088/1748-9326/aad965

Lovins House, Old Snowmass, Colorado (1982–83)

© Judy Hill

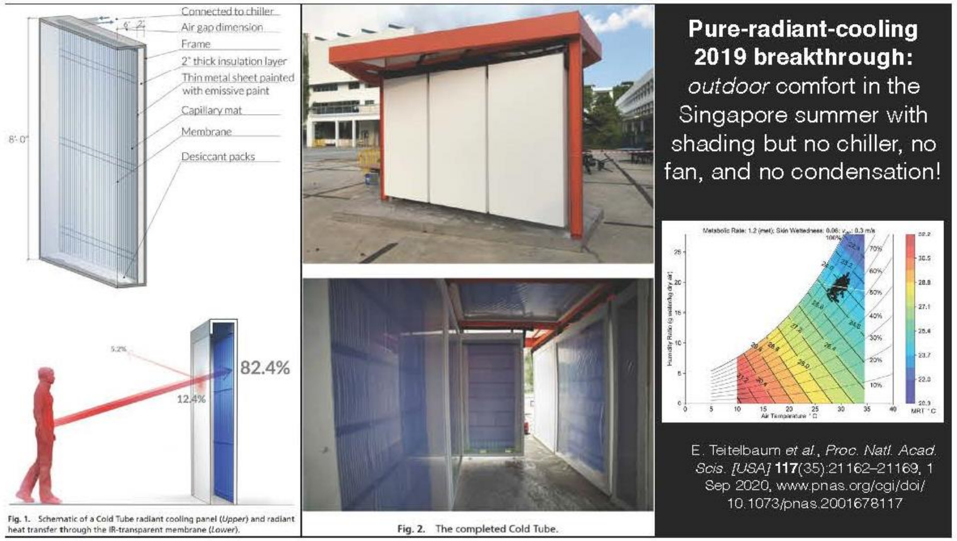
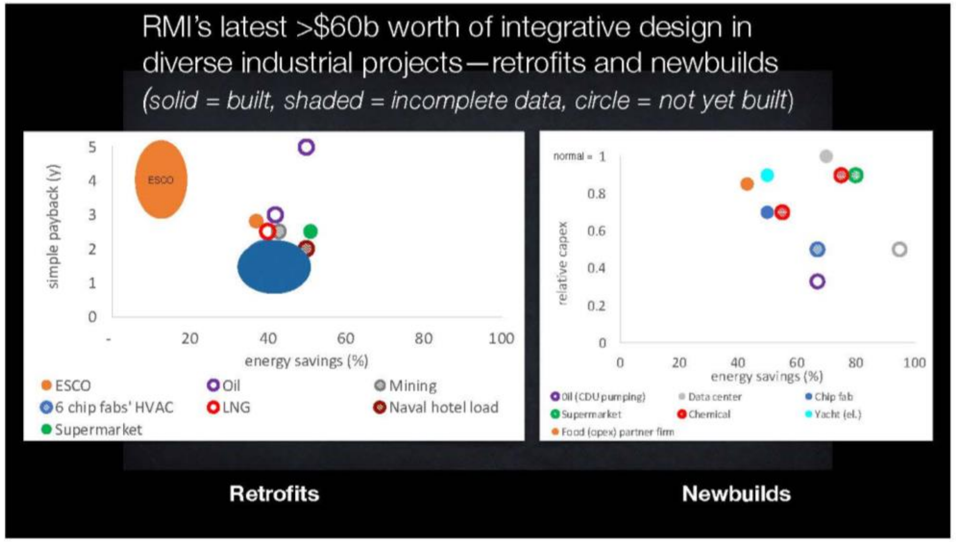


Fig. 1. Schematic of a Cold Tube radiant cooling panel (*Upper*) and radiant heat transfer through the IR-transparent membrane (*Lower*).

Fig. 2. The completed Cold Tube.

Pure-radiant-cooling 2019 breakthrough:
outdoor comfort in the Singapore summer with shading but no chiller, no fan, and no condensation!

E. Teitelbaum *et al.*, *Proc. Natl. Acad. Scis. [USA]* **117**(35):21162–21169, 1 Sep 2020, www.pnas.org/cgi/doi/10.1073/pnas.2001678117

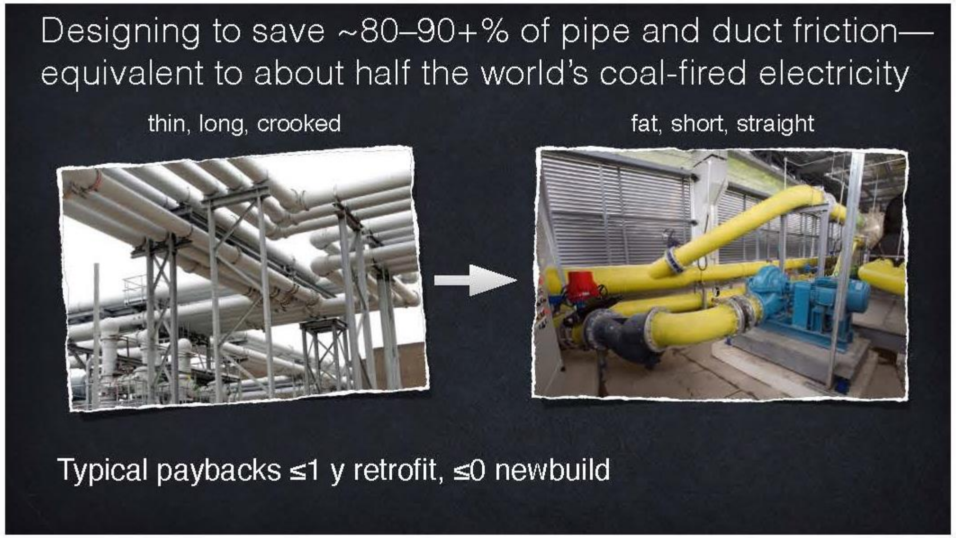


RMI's latest >$60b worth of integrative design in diverse industrial projects—retrofits and newbuilds
(solid = built, shaded = incomplete data, circle = not yet built)

Retrofits

Newbuilds

Naval efficiency opportunities

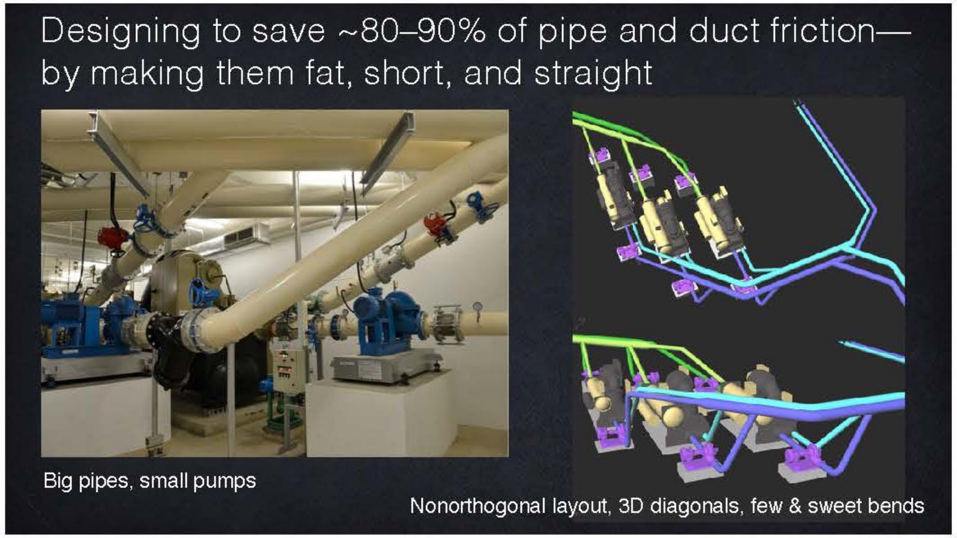


Designing to save ~80–90+% of pipe and duct friction—equivalent to about half the world's coal-fired electricity

thin, long, crooked

fat, short, straight

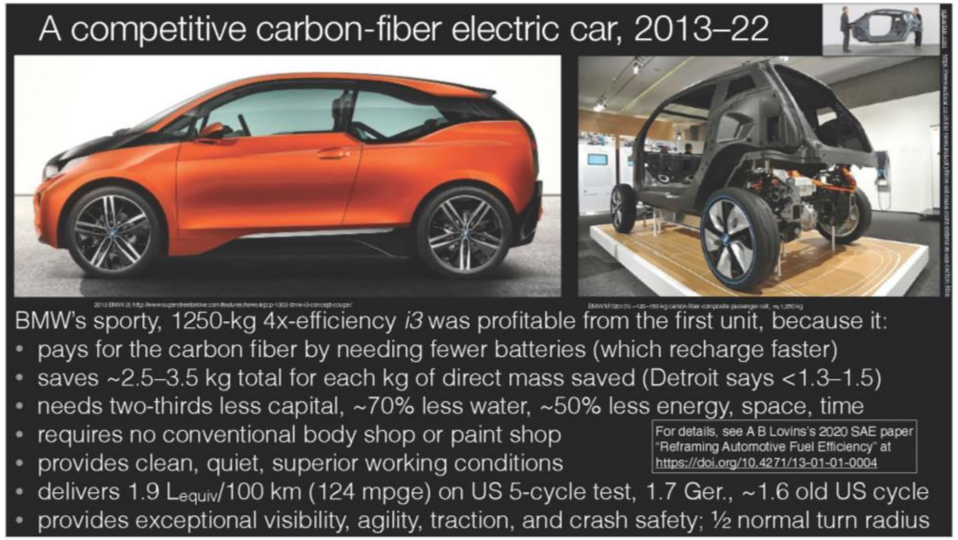
Typical paybacks ≤1 y retrofit, ≤0 newbuild



Designing to save ~80–90% of pipe and duct friction—by making them fat, short, and straight

Big pipes, small pumps

Nonorthogonal layout, 3D diagonals, few & sweet bends



A competitive carbon-fiber electric car, 2013–22

BMW's sporty, 1250-kg 4x-efficiency *i3* was profitable from the first unit, because it:

- pays for the carbon fiber by needing fewer batteries (which recharge faster)
- saves ~2.5–3.5 kg total for each kg of direct mass saved (Detroit says <1.3–1.5)
- needs two-thirds less capital, ~70% less water, ~50% less energy, space, time
- requires no conventional body shop or paint shop
- provides clean, quiet, superior working conditions
- delivers 1.9 L_{equiv}/100 km (124 mpge) on US 5-cycle test, 1.7 Ger., ~1.6 old US cycle
- provides exceptional visibility, agility, traction, and crash safety; ½ normal turn radius

For details, see A B Lovins's 2020 SAE paper "Reframing Automotive Fuel Efficiency" at https://doi.org/10.4271/13-01-01-0004

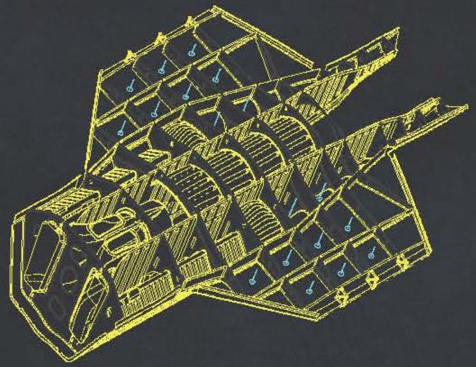
The revolution accelerates…

Tesla *Semi* Class 8 battery-electric truck (2022), >3× efficiency, 800-km full-load range (+ ~650 km w/30-minute recharge), 1.6-million-km warranty, 3–5× faster acceleration, 1/3-faster hill-climbing (5% grade), 2-y payback (could be 0 in this decade)

Celera *500L* (Otto Aviation 2020 prototype—the commercial version will add windows), *8× efficiency* (8–13 L/100 km *vs* ~78–118), >740 km/h, 8330-km range, 8× lower opex ($328/h); 6-seater can greatly scale up; H_2 & electrification underway

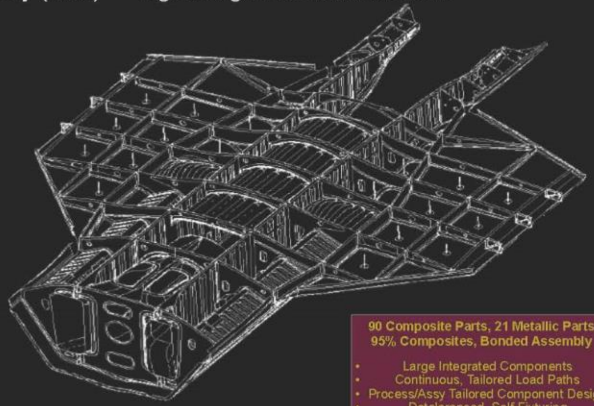
with more to come—the design approach can scale to regional-jet size, maybe 737

Advanced-composite airframes



95% carbon composite, 1/3 lighter, 2/3 cheaper

DARPA 1994–96: Integrated Design For Affordability (IATA) — Lightweight Tactical Airframe



90 Composite Parts, 21 Metallic Parts
95% Composites, Bonded Assembly

- Large Integrated Components
- Continuous, Tailored Load Paths
- Process/Assy Tailored Component Design
- Detoleranced, Self-Fixturing Bonded Assembly
- Functionality Attributes

Latest NASA version — 59× lighter than a "dumb" airplane wing

Structure as strong/tough as rubber but ~268× less dense (5.6 kg/m^3), made of thousands of identical injection-molded anisotropic parts, all covered by a tough polymer membrane of identical material, can yield any desired overall shape

An optimized-shape airplane that completely and continuously adapts *passively* to match flight conditions can thus be made stiff, strong, but scalable in manufacturing and in microrobotic assembly, needing no separate flight surfaces

4.27-m-wingspan model in NASA's high-speed wind tunnel worked better than predicted; applicable to wind turbines

N B Cramer et al 2019 Smart Mater. Struct. 28 055006, 01 April 2019, https://doi.org/10.1088/1361-665X/ab0ea2, http://mit.edu/archive/spotlight/shape-changing-plane-wing/, http://cba.mit.edu/docs/papers/19.03.MADCAT.pdf

Applications - Directed Fundamental Research ⟷ **Systems Engineering** ⟷ **Development and Deployment**

(Chemistry, Materials, Feasibility) (Component, Performance, Durability) (Process, Scaleup, Integration, Manufacturing)

UNIVERSITY OF
South Carolina

William Mustain, Professor and Associate Dean for Research
Jochen Lauterbach, Professor and Director of SC Center: SAGE
Sang Hee Won, Associate Prof., Mechanical and Aerospace Eng.

Areas of Interest and Strength:

Net-Zero Carbon Fuels

Carbon-Free E-Fuels (e.g. NH_3, H_2)

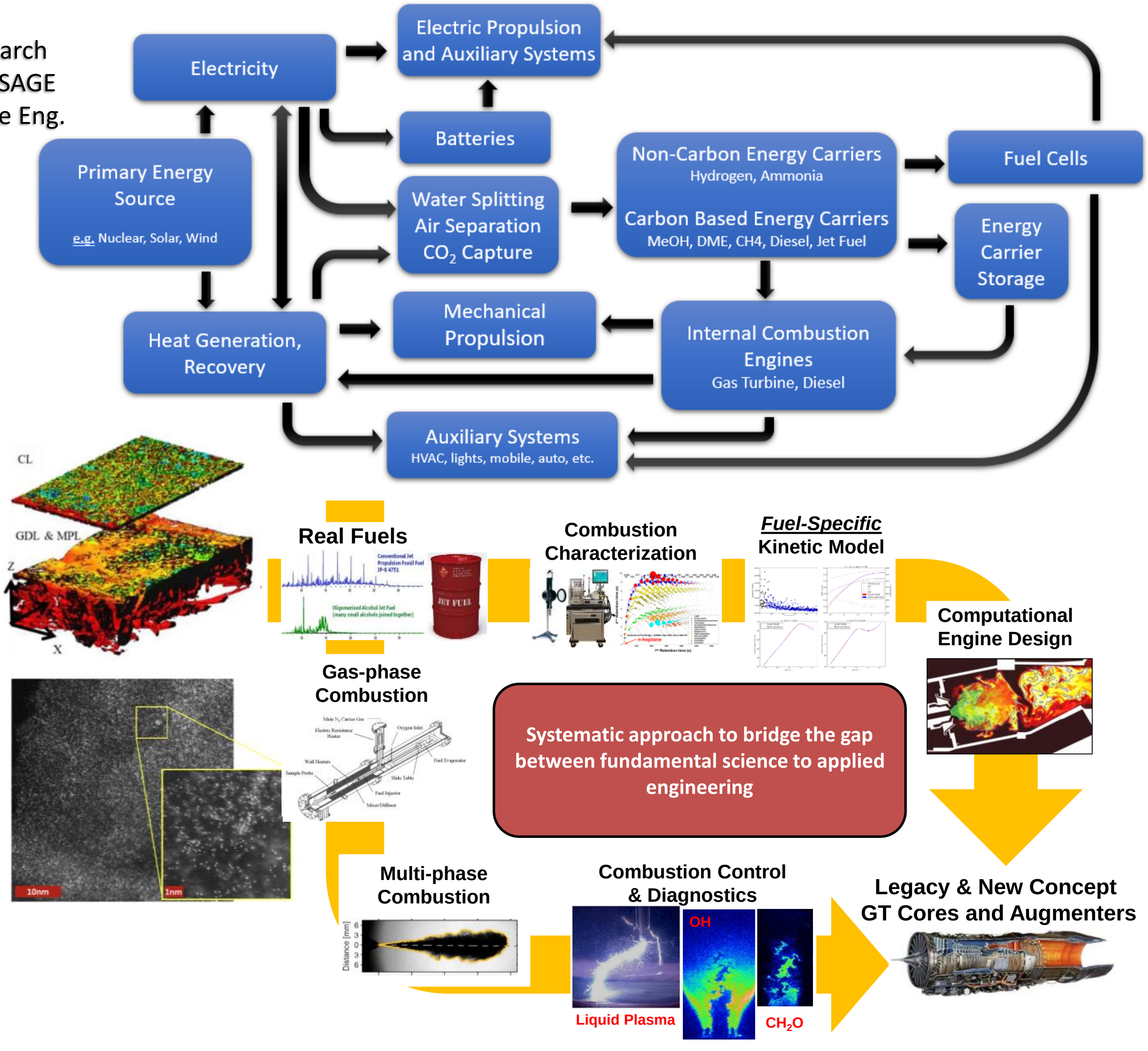
Digital Twins and Digital Ship Design

At-Sea Fuel Synthesis and Fuel Logistics

Combustion Property Characterization and Modeling

Electrochemical Energy Conversion and Storage

Multi-Scale Nuclear Power



Electricity

Electric Propulsion and Auxiliary Systems

Primary Energy Source
e.g. Nuclear, Solar, Wind

Batteries

Water Splitting
Air Separation
CO_2 Capture

Non-Carbon Energy Carriers
Hydrogen, Ammonia

Carbon Based Energy Carriers
MeOH, DME, CH4, Diesel, Jet Fuel

Fuel Cells

Energy Carrier Storage

Heat Generation, Recovery

Mechanical Propulsion

Internal Combustion Engines
Gas Turbine, Diesel

Auxiliary Systems
HVAC, lights, mobile, auto, etc.

Real Fuels

Combustion Characterization

Fuel-Specific Kinetic Model

Computational Engine Design

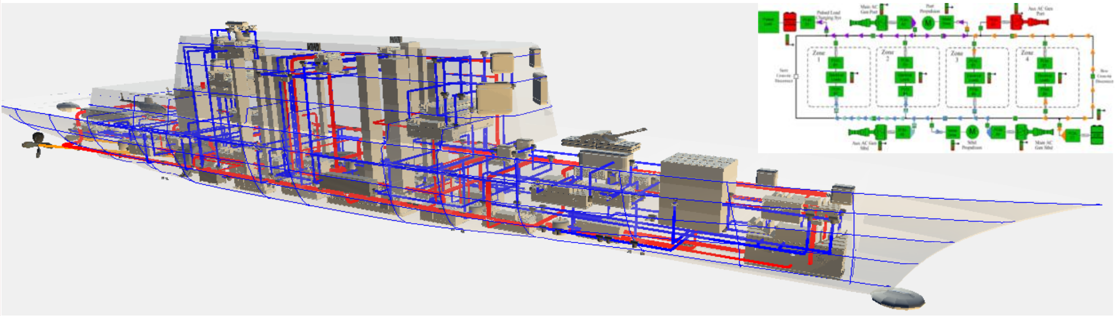
Gas-phase Combustion

Systematic approach to bridge the gap between fundamental science to applied engineering

Multi-phase Combustion

Combustion Control & Diagnostics

Legacy & New Concept GT Cores and Augmenters



U.S. Naval Academy

Faculty Interest and Expertise with Current Facilities and Activities

Energy Conversion

- USN-relevant combustion platforms
  - helicopter-scale gas turbine
  - Single- and multi-cylinder diesel engines (Cummins 6.7L)
  - AMG HMMWV engine
- Waste-heat recovery
- Fuels testing with ammonia, SAF, bio-based integration USN diesel systems
- Wave-energy conversion
- Waste-to-energy
- Wind and tidal turbine energy

Materials Characterization

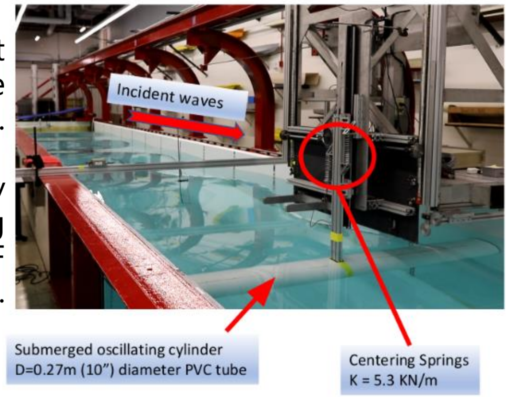
- Optical and scanning electron microscopy
- Corrosion testing for materials
- Coatings analysis
- MTS/Instron mechanical testing

Control and Optimization of Electrical Power Systems

Energy Security and Sustainability

Interdisciplinary course development focused on sustainability and carbon-free energy

USNA 1-DOF Undamped Oscillator Design



120 ft and 380 ft towing tank, wave generation.

Wave-energy absorption test rig shown (current NSF grant).

Single and multi-cylinder USN-relevant diesel engines, waste-heat recovery; 6.7L Cummins diesel (USN small craft); legacy AMG HMMWV diesel engine.

Optical visualization of diesel combustion.

USNA Mission and Midshipmen Engagement

To develop Midshipmen morally, mentally and physically …to assume the **highest responsibilities of command, citizenship and government**.

Current and future midshipmen's careers will roughly span decarbonization effort to 2050.

Proposed midshipmen involvement:

- Internships with partner institutions
- Capstone engineering design projects
- Research projects
- Course development related to decarbon efforts (ongoing now)

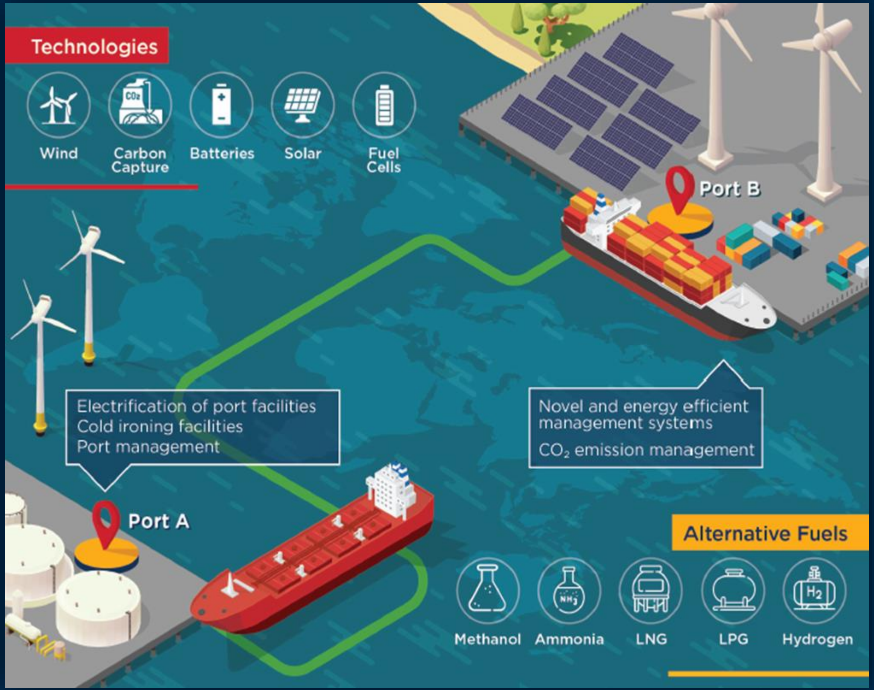
Recent fleet related applied engineering design projects:

Redesign and testing of aircraft tie down points on DDG

Design of microgrids for NSA Souda Bay (Crete) and USN Autec (Bahamas)

About ABS

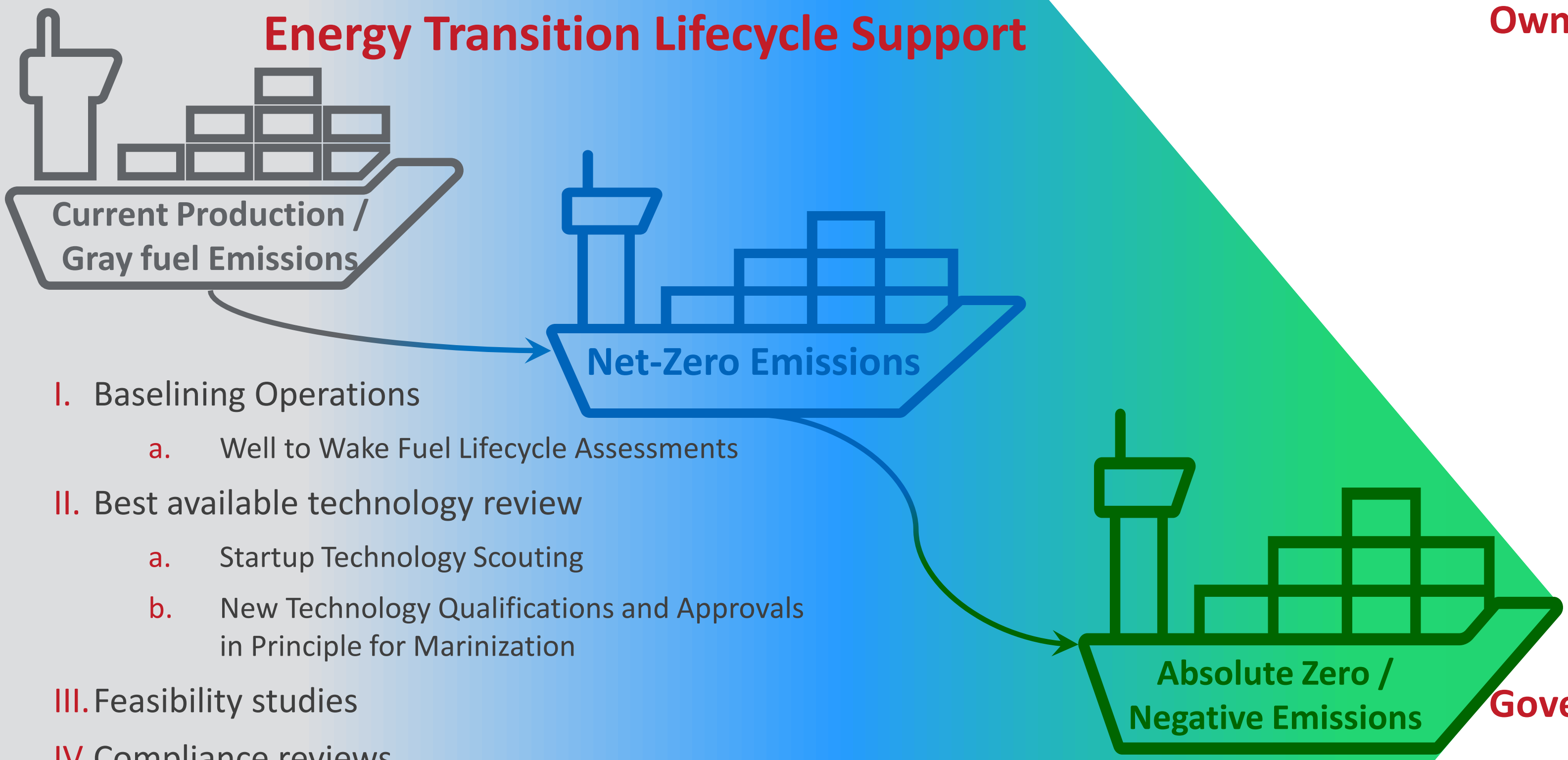
The mission of ABS is to serve the public interest as well as the needs of our members and clients by promoting the security of life and property and preserving the natural environment



- Founded in 1862 by 9 U.S. marine insurance companies
- A 501c(6) Non-Profit Marine Classification Society
- No owners/shareholders, ABS Board of Directors are appointed from its Members
- ABS Members are the owners, operators, designers and builders of ships, offshore units and associated equipment
- ABS as a class society represents industry and helps:
  - Design
  - Construction
  - Operational maintenance
- Headquarters – Houston, Texas
- Employees: 4,000 globally, 1,300 U.S.
- 200 offices in 70 countries

ABS - Maritime Energy Transition

Energy Transition Lifecycle Support



I. Baselining Operations
   a. Well to Wake Fuel Lifecycle Assessments
II. Best available technology review
   a. Startup Technology Scouting
   b. New Technology Qualifications and Approvals in Principle for Marinization
III. Feasibility studies
IV. Compliance reviews
V. Prototype and Demonstration Projects
VI. Develop Standardized Practice for Scaling-up and repeatability
   a. Clean Energy Marine Hubs
   b. Green Shipping Corridors
VII. CapEx and Financial Planning (investment, fundraising, grants)
VIII. Classing of Alternative Fuel Vessels

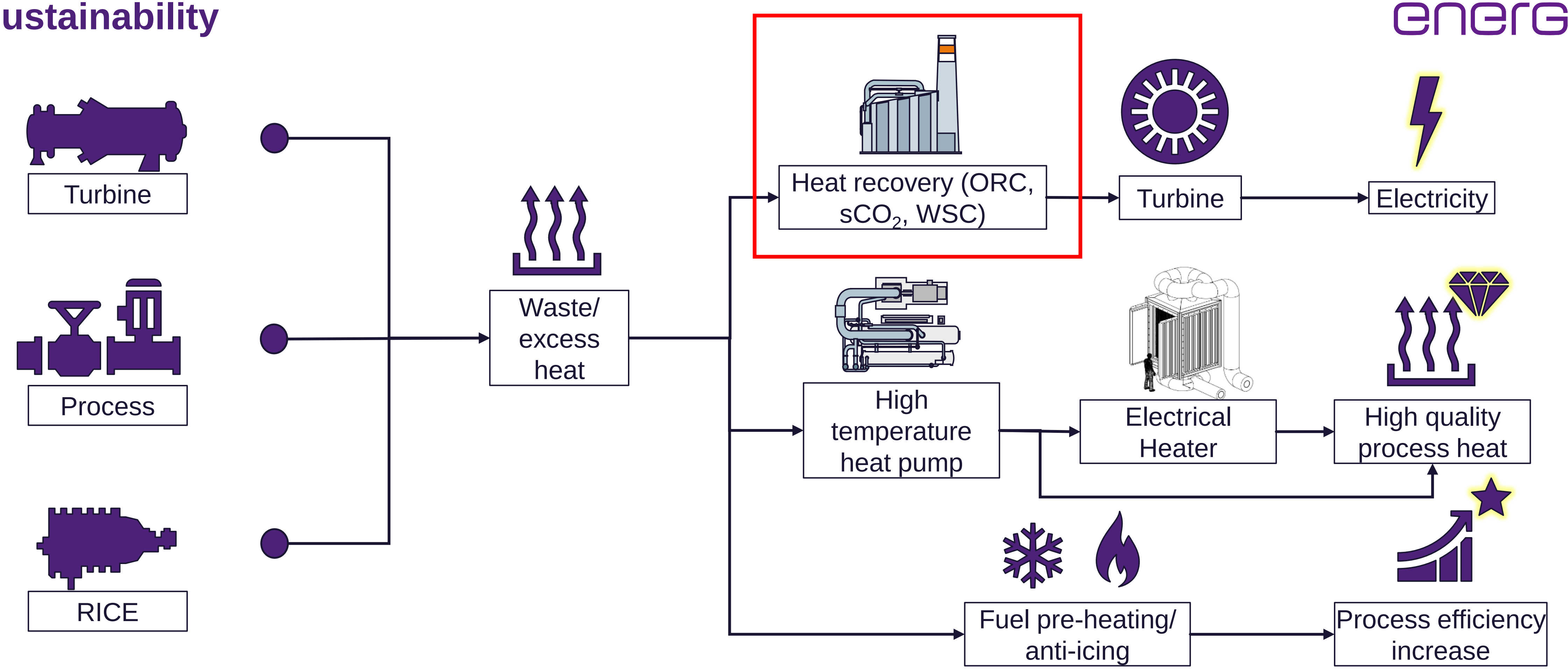
Owners and Operators:

- Short-Term
  - Develop Decarbonization Business Strategy and Timelines Based on Pathway Options and Technologies
  - Leverage ESG as a Management Tool, Not a Compliance Tool
  - Implement Digitalization as Immediate Solution to Improve Fuel Consumption and Performance
- Mid-Term
  - Focus on Behavioral Changes
  - Apply Greater Use of Data and Simulation
  - Invest in People and Training
- Long-Term
  - Understand Carbon Economics
  - Recognize Pivotal Role of Hydrogen and Carbon Value Chains

Governments:

- Support Investments to Provide Scalability While De-Risking Options
- Policies/Regulation Implementation to Drive Energy Transition Outcomes;
- Address Boundary Conditions – Safety, Ports, Fuel Availability and Cost
- Incentivize Maritime Innovation R&D and Demonstration Projects

Waste Heat Recovery for Improved Efficiency and Environmental Sustainability



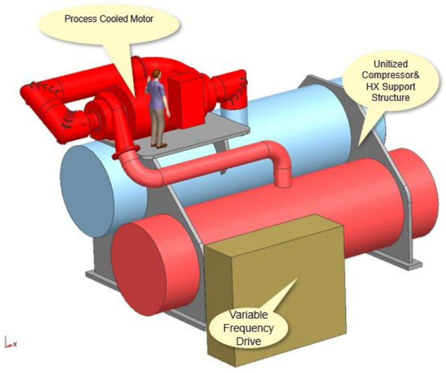
ORC – Organic Rankine Cycle; sCO_2 – Supercritical carbon dioxide; WSC – Water Steam Cycle; RICE: Reciprocating Internal Combustion Engine

1) derived from Bianchi et al., Estimating the waste heat recovery in the European Union Industry; 2019

Active Technology Development

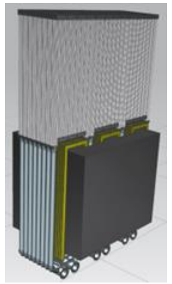
Carbon Capture
- Direct Air Capture
- Point of Combustion Capture

Heat Pumps
- Low temperature
- High Temperature
- High Power Density Hermetic

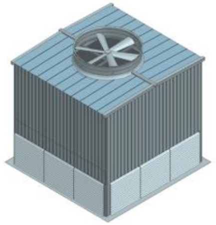


Enabling SE Technologies
- Electric Heaters: in-house
- HPD motors/generators: in-house
- Electrolyzers: partnership
- E-Fuels : partnership

SE Vision: Local/off-shore Fuel Production

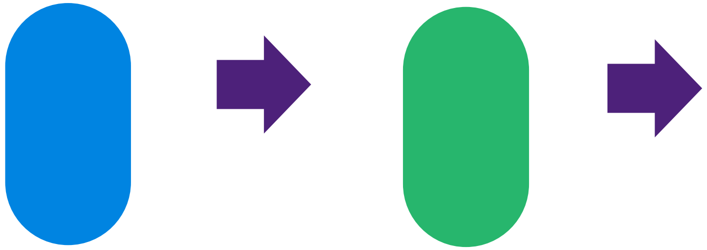


E-heater → steam/water



DAC→ CO2

Electrolyzer → H2



Electric Reformer

Fischer-Tropsch Reactor

- ❖ Diesel
- ❖ Jet
- ❖ Gasoline

U.S. DOT Maritime Administration

Office of Environment and Innovation
Program Brief

Daniel Yuska – Director, Office of Environment and Innovation

Two Primary Functions

- **Manage the Maritime Environmental and Technical Assistance (META) Program**
  - Technical Assistance is broadly interpreted to include needed RD&T and technology demonstration and verification
  - Main topic areas of focus since inception
    - Port/vessel emissions/multimodal modeling/decarbonization
    - Aquatic nuisance species (ballast water/hull fouling)
    - Vessel-generated underwater noise
    - Safety
- **Support Domestic and International Maritime Environmental Policy**
  - Partnerships with US agencies
  - International engagements (IMO/ISO)

More on META…

- Technology and innovation program that performs research, demonstration, and data gathering
- Collaboration w/other government agencies, industry stakeholders, NGOs, academia
  - U.S. Federal partners include: DOE, USCG, EPA, Navy, NOAA, National Labs, DOT Modes
- Focus areas: criteria pollutant and GHG emissions reductions, alternative and renewable fuels, energy efficiency applications, green technologies (fuel cells, batteries), multimodal modeling, control of aquatic nuisance species, vessel-generated underwater noise
- Results: peer-reviewed articles, white papers, industry guidance
  - Informs regulatory/policy actions
  - Informs industry on “what works”
- https://www.maritime.dot.gov/innovation/meta/maritime-environmental-and-technical-assistance-meta-program

Highlights of META Projects

Maritime Decarbonization

Current Projects

- **Vessel Energy Efficiency and Decarbonization Guide**
- **Microgrid Demonstration (port focused)**
- **Smartships GHG Emissions Calculator**
- **Battery Electric Workboat Techno-economic Analysis**
- **Vessel Carbon Capture and Storage Study/TEA/Demo**
- **Future Energy Options Studies**
  - Great Lakes
  - California
  - Gulf Coast/Lower Mississippi
- **Lifecycle Emissions Analysis**
  - ICE vs Battery Electric, Methanol, LNG
- **Blue Carbon Study (port focused)**
- **Low Carbon Fuel Testing on Marine Engines**

Decarbonization Research Consortium

Path Forward

March Meetings x2

Homework & Dialogue between meetings
Questions & Requests for Information

Identify Priority Research Areas & Gaps
Determine Roadmap Model
Research/Writing

Determine Day/Time for future meetings
In-person meetings – when/where