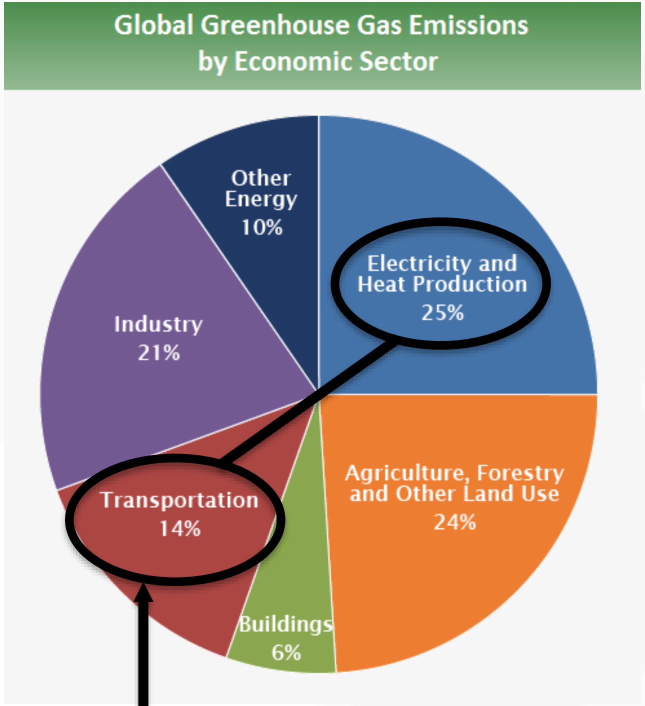
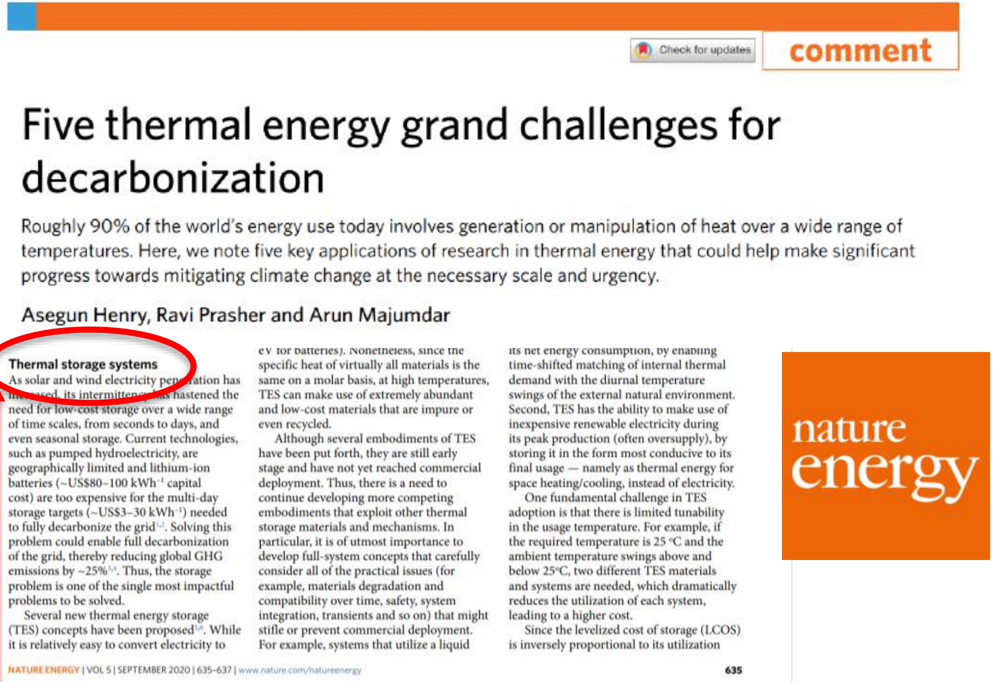
# Technologies for Deep Decarbonization Using High Temperature Liquid Metal

Asegun Henry, Ph.D.
Noyce Career Development Chair
Associate Professor
Department of Mechanical Engineering
Massachusetts Institute of Technology

# Energy Storage Impact




Energy storage is the key to decarbonizing electricity and transportation



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## Five thermal energy grand challenges for decarbonization

Roughly 90% of the world's energy use today involves generation or manipulation of heat over a wide range of temperatures. Here, we note five key applications of research in thermal energy that could help make significant progress towards mitigating climate change at the necessary scale and urgency.

Asegun Henry, Ravi Prasher and Arun Majumdar

**Thermal storage systems**

As solar and wind electricity penetration has increased, its intermittency has hastened the need for low-cost storage over a wide range of time scales, from seconds to days, and even seasonal storage. Current technologies, such as pumped hydroelectricity, are geographically limited and lithium-ion batteries (~US$80–100 $kWh^{-1}$ capital cost) are too expensive for the multi-day storage targets (~US$3–30 $kWh^{-1}$) needed to fully decarbonize the grid[1,2]. Solving this problem could enable full decarbonization of the grid, thereby reducing global GHG emissions by ~25%[3,4]. Thus, the storage problem is one of the single most impactful problems to be solved.

Several new thermal energy storage (TES) concepts have been proposed[5,6]. While it is relatively easy to convert electricity to

eV for batteries). Nonetheless, since the specific heat of virtually all materials is the same on a molar basis, at high temperatures, TES can make use of extremely abundant and low-cost materials that are impure or even recycled.

Although several embodiments of TES have been put forth, they are still early stage and have not yet reached commercial deployment. Thus, there is a need to continue developing more competing embodiments that exploit other thermal storage materials and mechanisms. In particular, it is of utmost importance to develop full-system concepts that carefully consider all of the practical issues (for example, materials degradation and compatibility over time, safety, system integration, transients and so on) that might stifle or prevent commercial deployment. For example, systems that utilize a liquid

its net energy consumption, by enabling time-shifted matching of internal thermal demand with the diurnal temperature swings of the external natural environment. Second, TES has the ability to make use of inexpensive renewable electricity during its peak production (often oversupply), by storing it in the form most conducive to its final usage — namely as thermal energy for space heating/cooling, instead of electricity.

One fundamental challenge in TES adoption is that there is limited tunability in the usage temperature. For example, if the required temperature is 25 °C and the ambient temperature swings above and below 25 °C, two different TES materials and systems are needed, which dramatically reduces the utilization of each system, leading to a higher cost.

Since the levelized cost of storage (LCOS) is inversely proportional to its utilization

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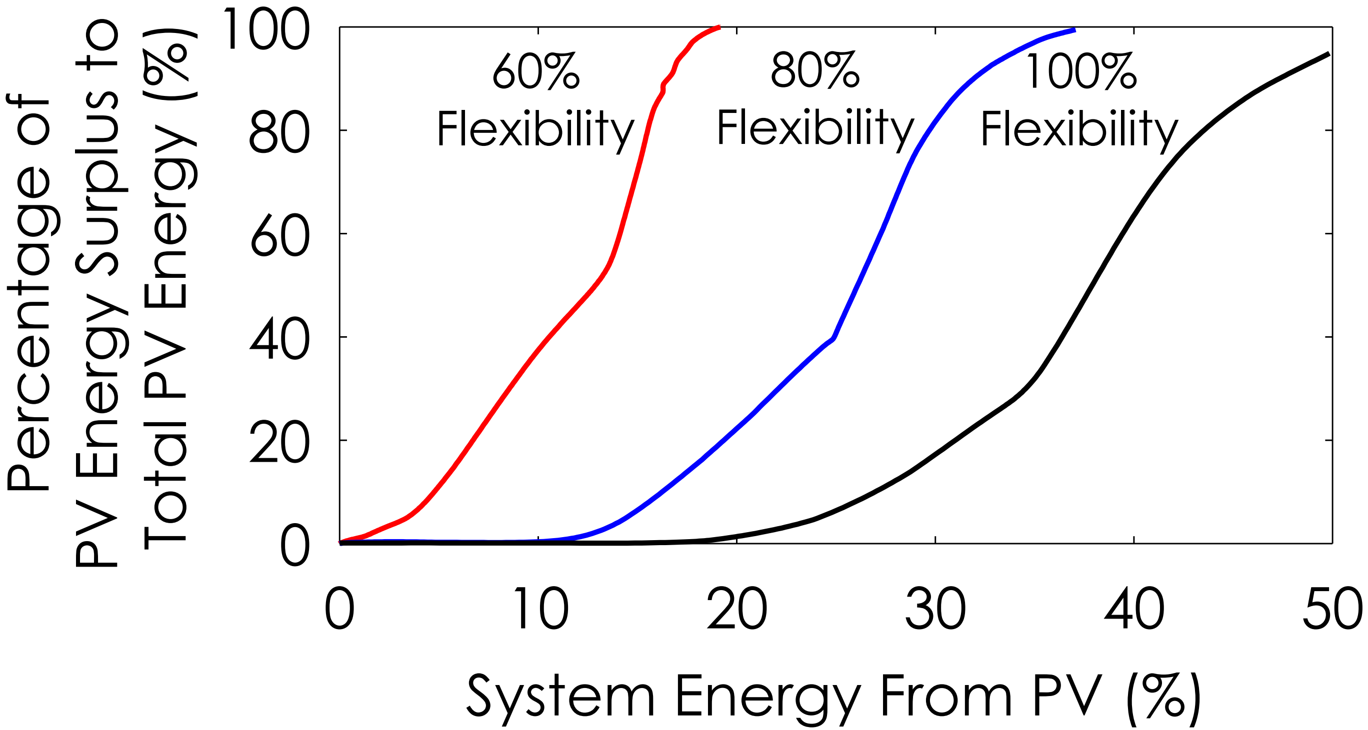
635

More details in my recent paper:
A. Henry, R. Prasher, A. Majumdar, Nat Energy 5, 635–637 (2020)

# The Storage Problem




P. Denholm, R. Margolis, Energy Policy, 35, 2852–2861 (2007)

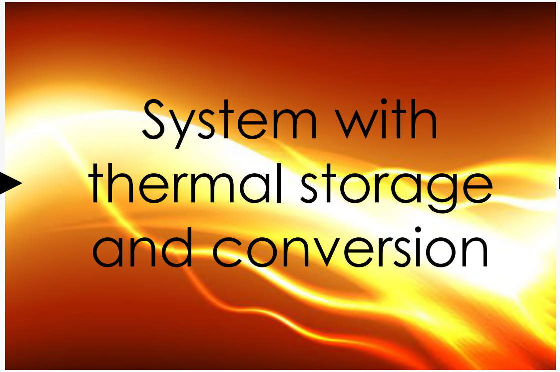
# What is Thermal Energy Grid Storage (TEGS)?

Electricity → Heat (storage) → Electricity

Electricity in

Electricity out

Like a battery

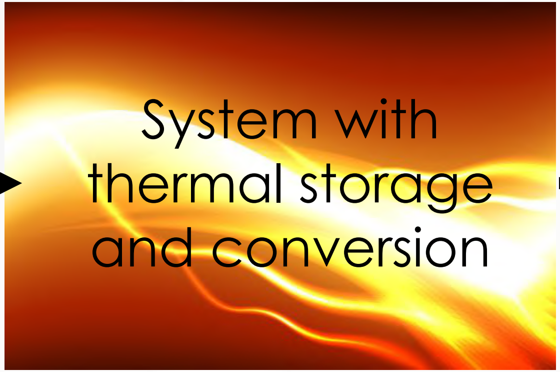


# A Thermodynamic Crime!

Electricity → Heat (storage) → Electricity

Why would anyone ever do this?

Storing heat can be 10-100X cheaper than storing electricity!

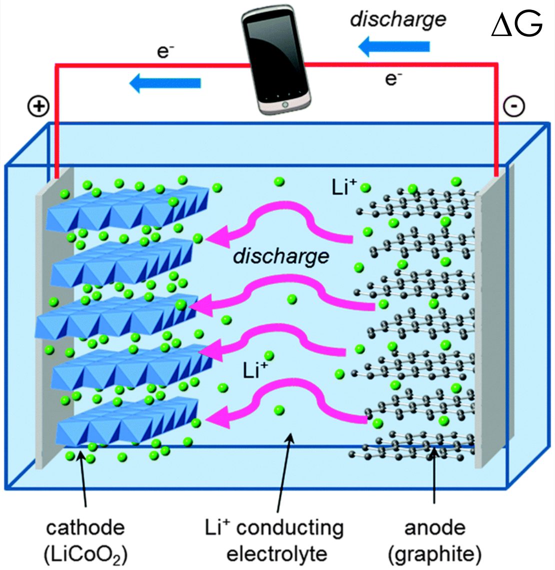



Can be 100% efficient going from lower to higher entropy

Can never be 100% efficient going from higher to lower entropy

# Why is it so cheap? – Atomistic Insight

Low concentration of active species
Large energy per active atom
Special, pure, organized materials
Impurities and byproducts are bad




250-695 kWh/$m^3$ **$150-400/kWh**

100% concentration of active species
Low energy per active atom
Disordered, simple scrap material
Impurity tolerant

300-600 kWh/$m^3$ **$4-77 kWh**

# Simple Estimate

Liquid silicon storage
$C_p$ = 950 J $kg^{-1}$ $K^{-1}$
Cost = $1.5/kg
$\Delta T$ = 500°C

Cost/Energy = $1.5/kg ÷ ($C_p * \Delta T$) =
$11.4/kWh-t
At 50% efficiency
Cost/Energy = $11.4/kWh ÷ 0.5 =
**$22.8/kWh-e**

Liquid iron storage
$C_p$ = 444 J $kg^{-1}$ $K^{-1}$
Cost = $0.11/kg
$\Delta T$ = 500°C

Cost/Energy = $0.11/kg ÷ ($C_p * \Delta T$) =
$1.8/kWh-t
At 50% efficiency
Cost/Energy = $1.8/kWh ÷ 0.5 =
**$3.6/kWh-e**

# Heat Leakage?

**Volume to surface area ratio**

$\tau$ = m*Cp*R = $\rho$*V*Cp*L/kA

For tanks of order 10 m

$\tau$ on the order of months

Lose $\leq$ 1% of energy stored per day

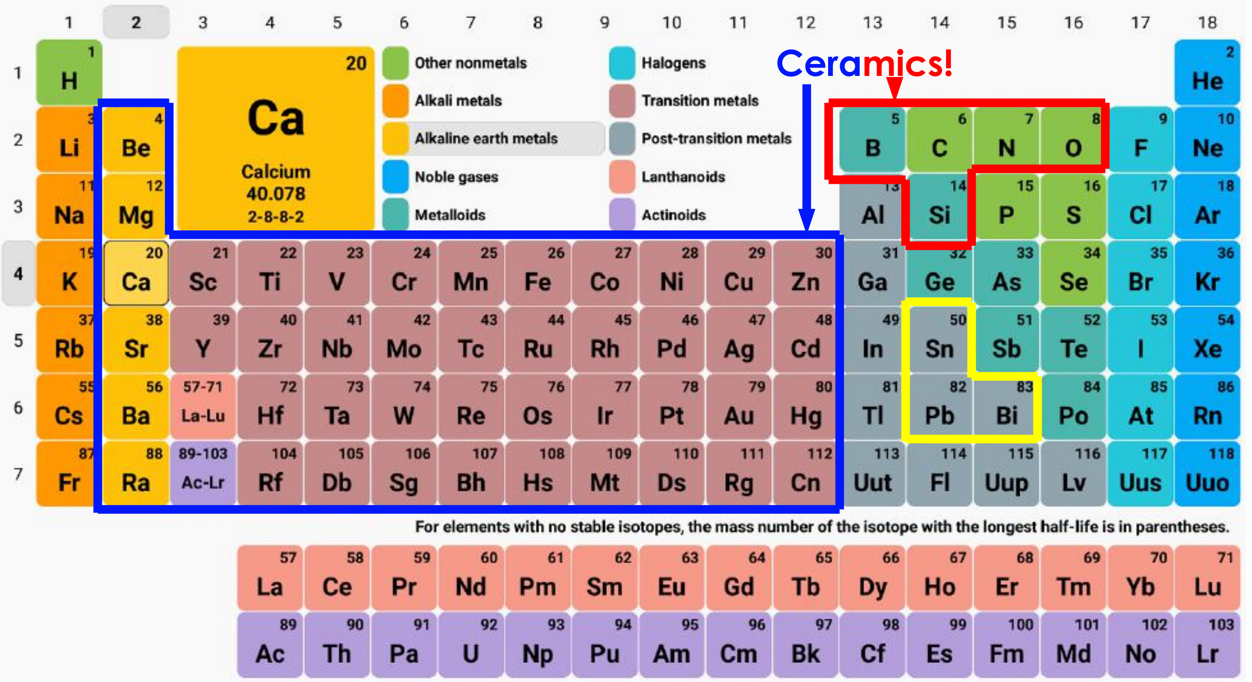
# What Materials? - Atomistic Insight

What about corrosion?
The hotter the faster/worse!

Si melts at 1414°C

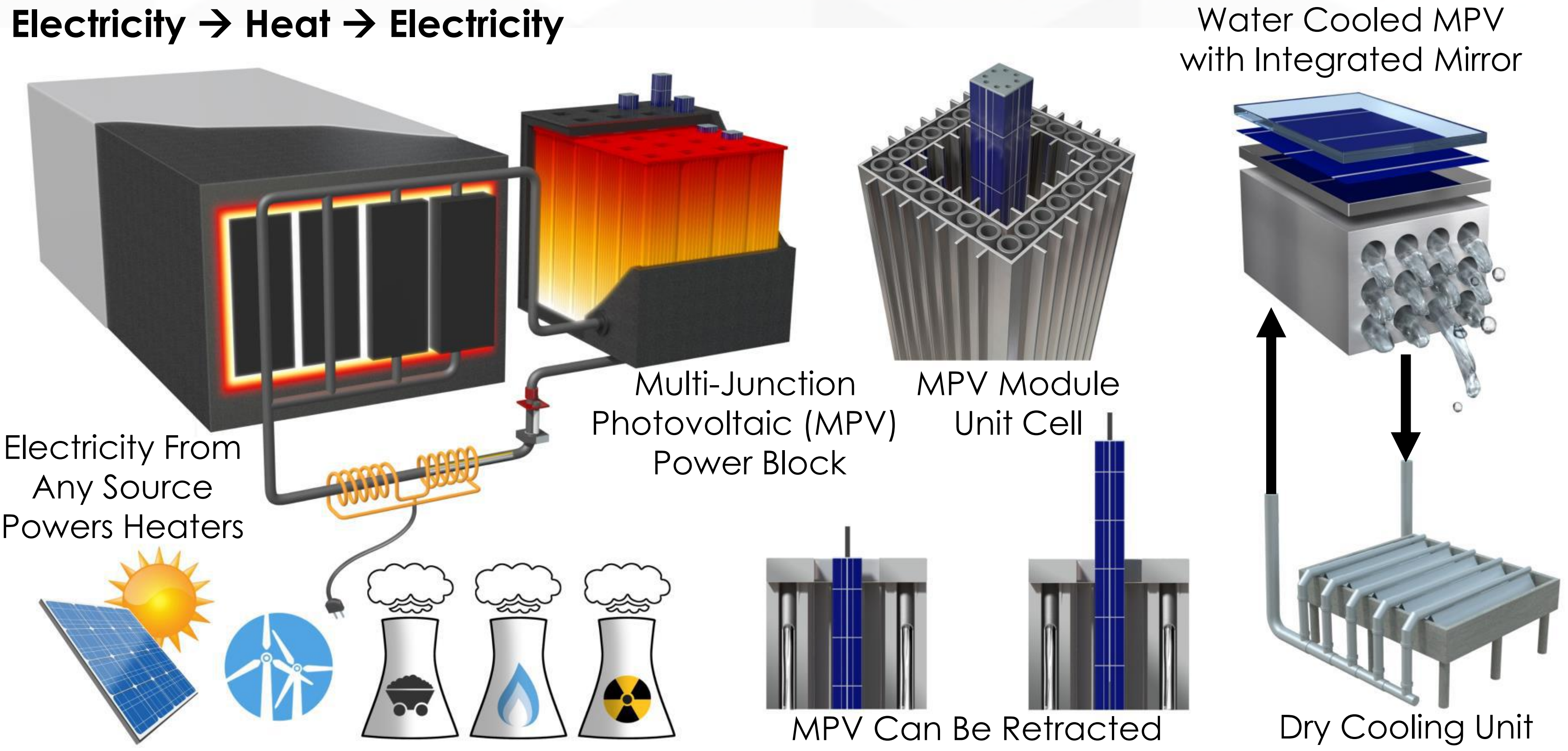
Fe melts at 1538°C

Molten metal dissolves metal
Like
Sugar water dissolves sugar

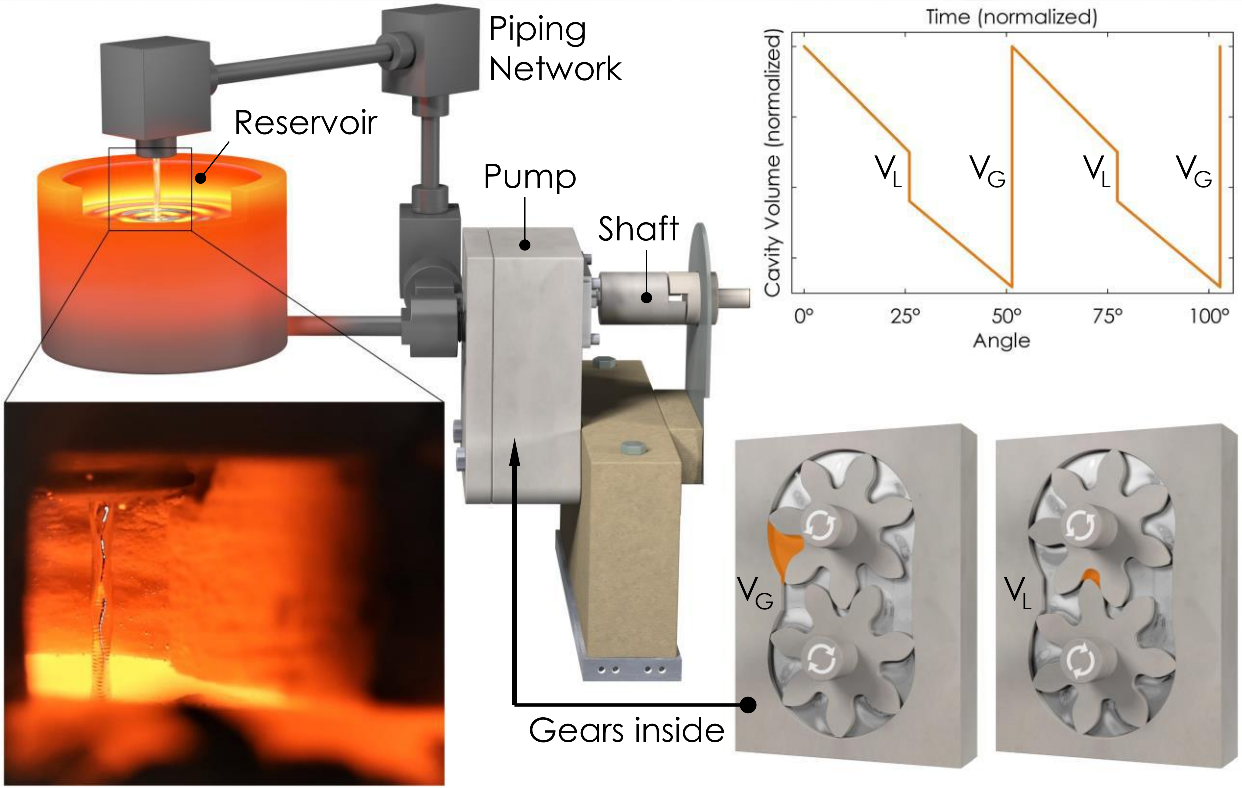



Key New Idea = Liquid Metal + Ceramics

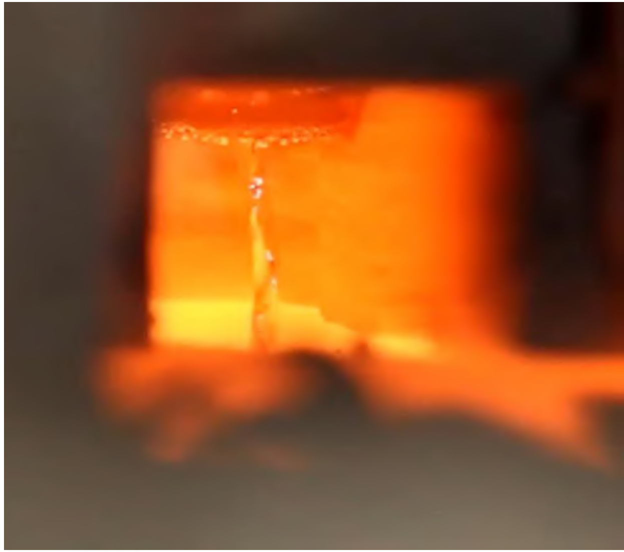
# "Sun in a Box" TEGS-MPV



# How Are You Going To Pump It?




Pumping at 1350°C



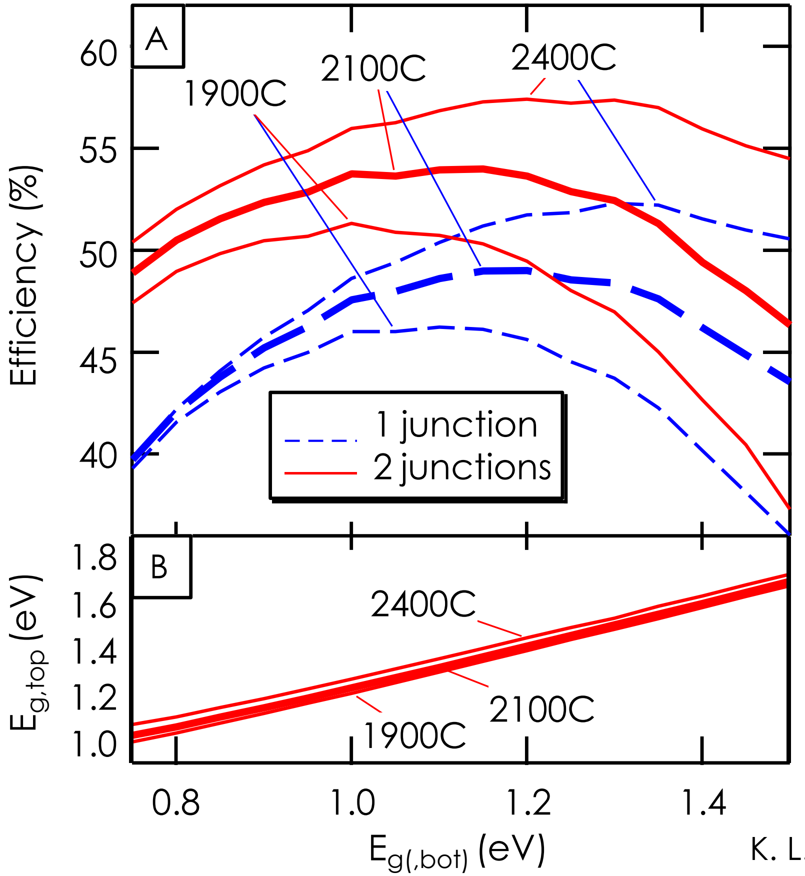
C. Amy et al., Nature 550, 199–203 (2017)

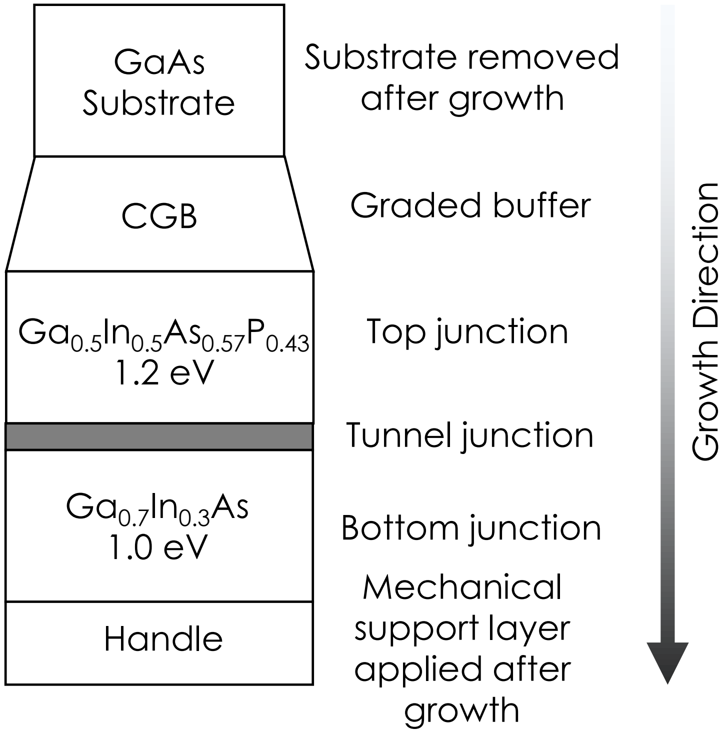
# Why Use MPV Instead of a Turbine?

- Turbine
  - Doesn't currently exist
  - **Large barrier to new turbine deployment**
  - > $100M of R&D
  - New materials + New HXs
  - Min-Hour response time to full load
- MPV
  - **Much lower barrier to deployment**
  - **Lower cost < $0.5/W-e**
  - Similar efficiency (50-55%)
  - Fast response time (seconds)
  - Fundamentally new cost/learning curve
  - Lower maintenance

Turbomachinery
vs.
MPV

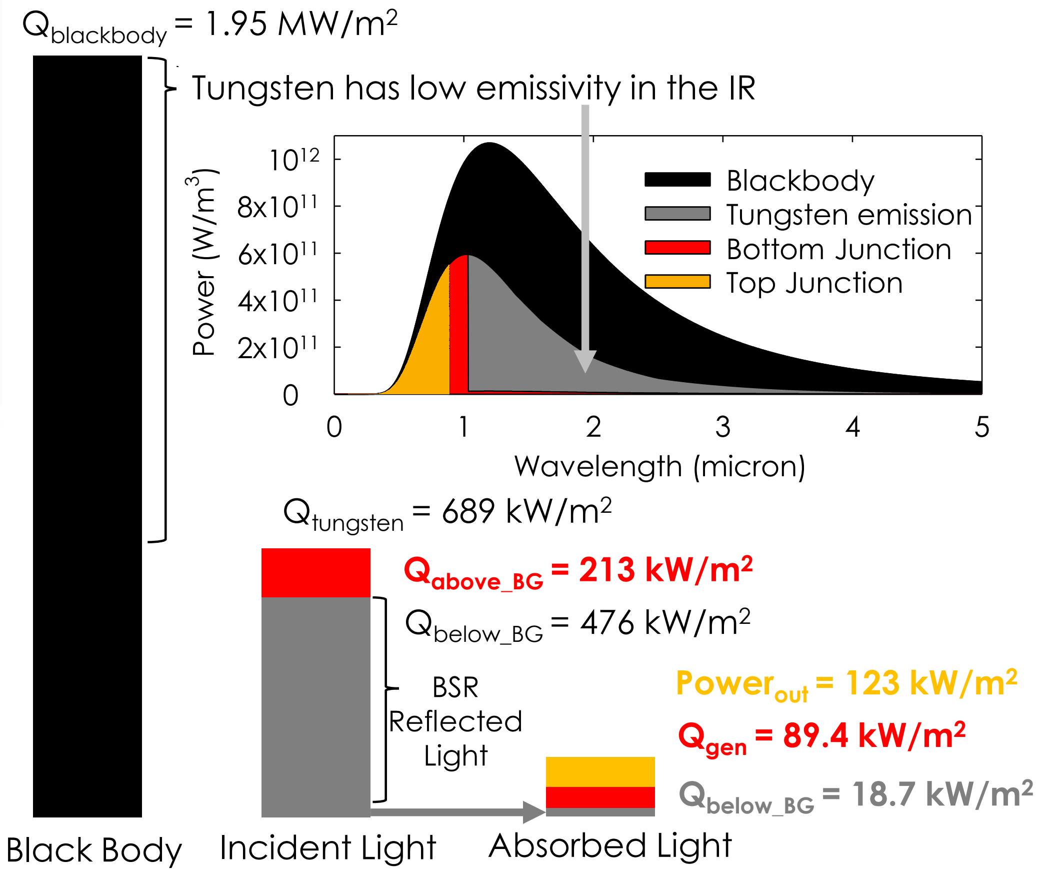
# Why Multi-Junction Photovoltaics?




K. L. Schulte et al., Journal of Applied Physics 128, 143103 (2020)

# System Efficiency



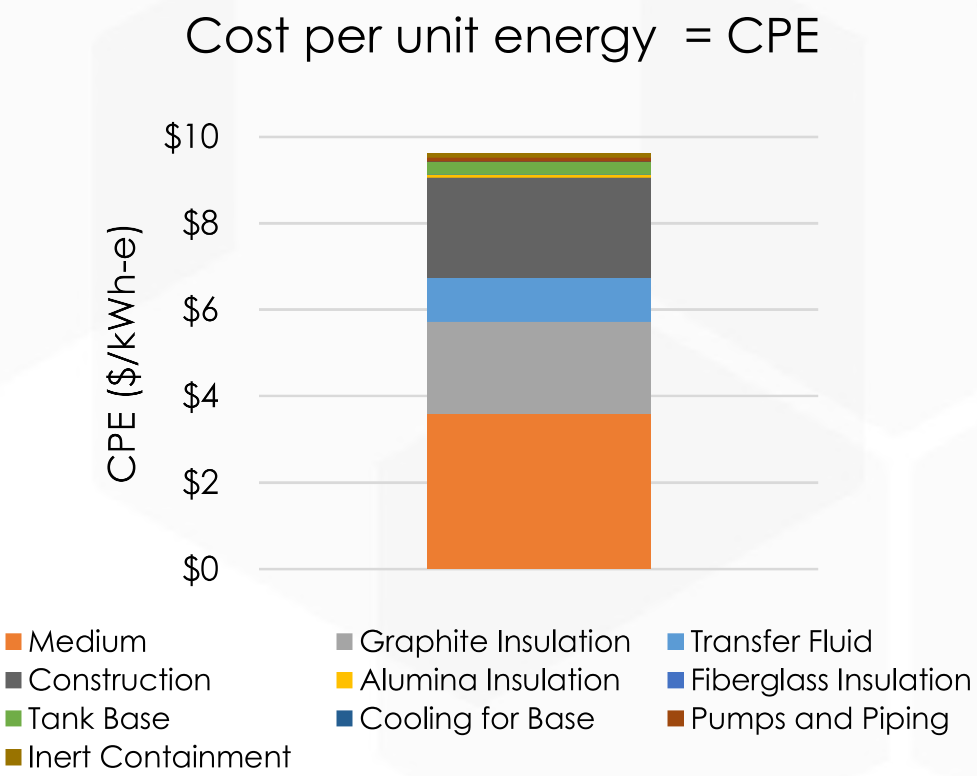

Efficiency = $Power_{out}$ ÷ Qtotal = 123 ÷ (123 + 89.4 + 18.7 + 4.6) = **52%**

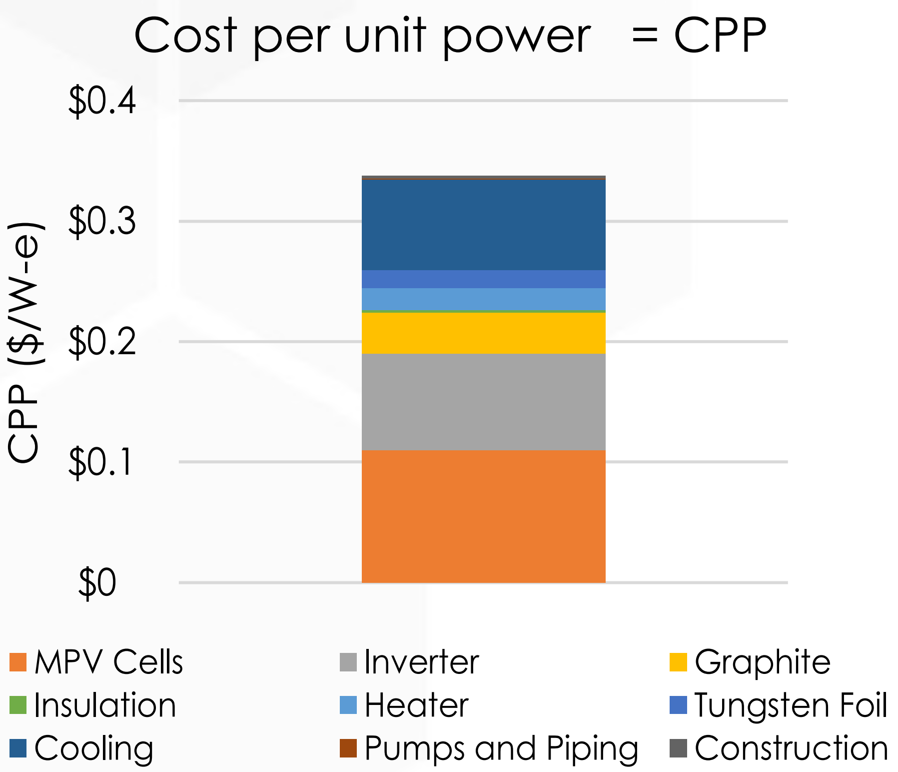
- <1% loss in electronics for heater
- ~1%/day loss in heat leakage
- <1% loss in parasitic load
- ~ 50% roundtrip efficiency (RTE)

C. Amy et al., Energy & Environmental Science, 12, 334 (2019)

# System Cost

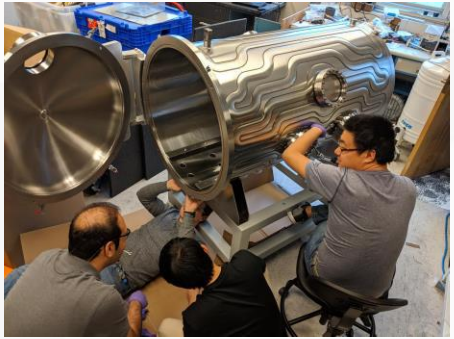
Cost = CPE*time + CPP

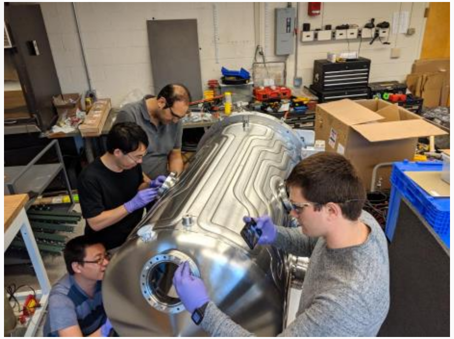


# What's Next?

- ARPA-E Project
- **Build a prototype**
- Pumping
- 2500°C Heaters
- Emitter evaporation/deposition
- Cell redesign/optimization + fabrication
- High current density
- High reflectivity (> 98%)
- High efficiency(≥ 50%)
- Long term testing





# Hydrogen Production from Methane

**All Gases**

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

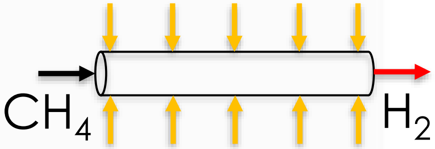
$$CO + H_2O \rightarrow CO_2 + H_2$$

**<u>S</u>**team **<u>M</u>**ethane **<u>R</u>**eforming (SMR)
+
**<u>W</u>**ater-**<u>G</u>**as **<u>S</u>**hift (WGS)

Gas + **<u>Solid</u>** Products

$$CH_4 \rightarrow C + 2H_2$$

Direct Thermal Pyrolysis



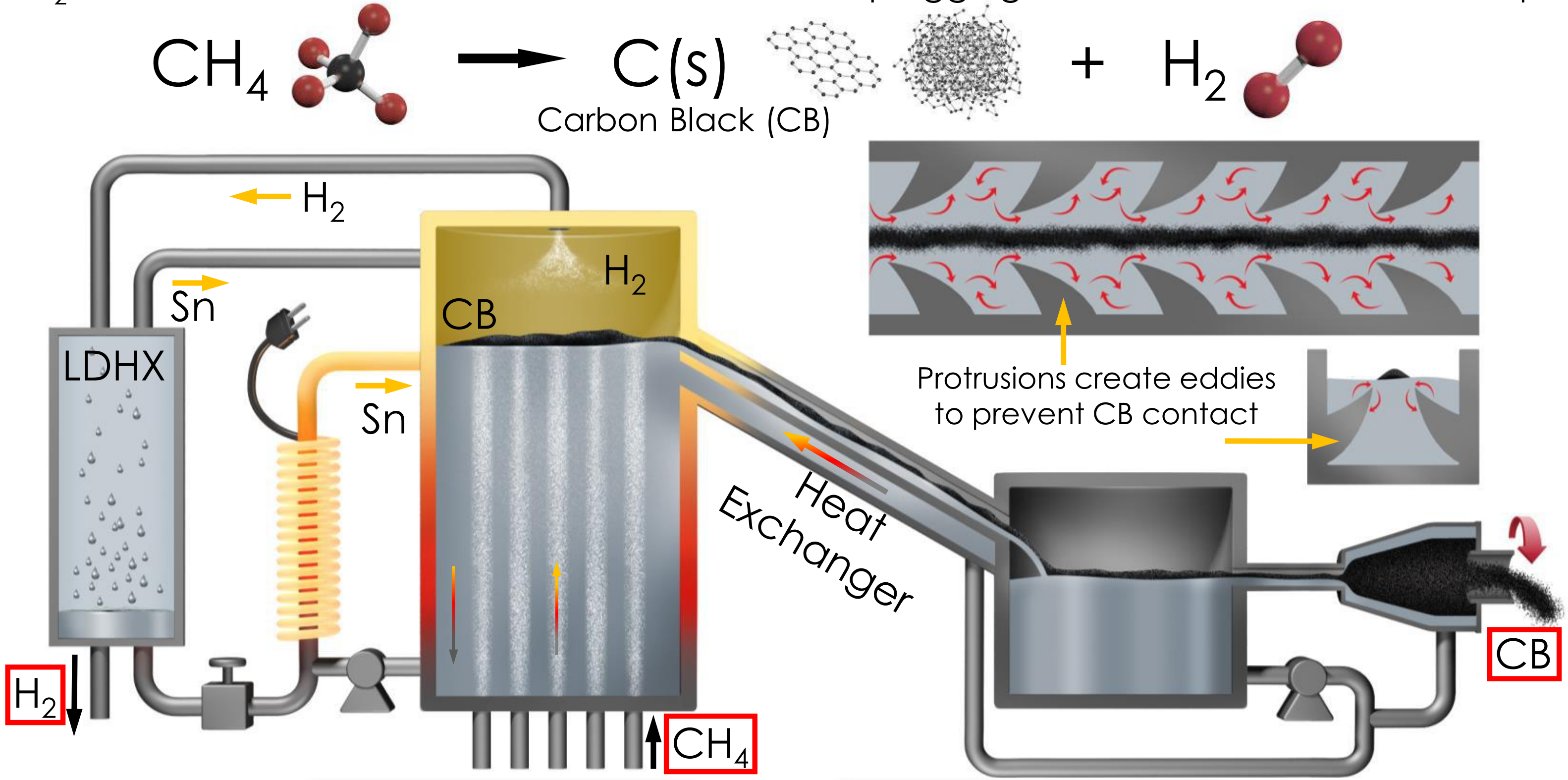

The plugging problem

# The Reactor Concept

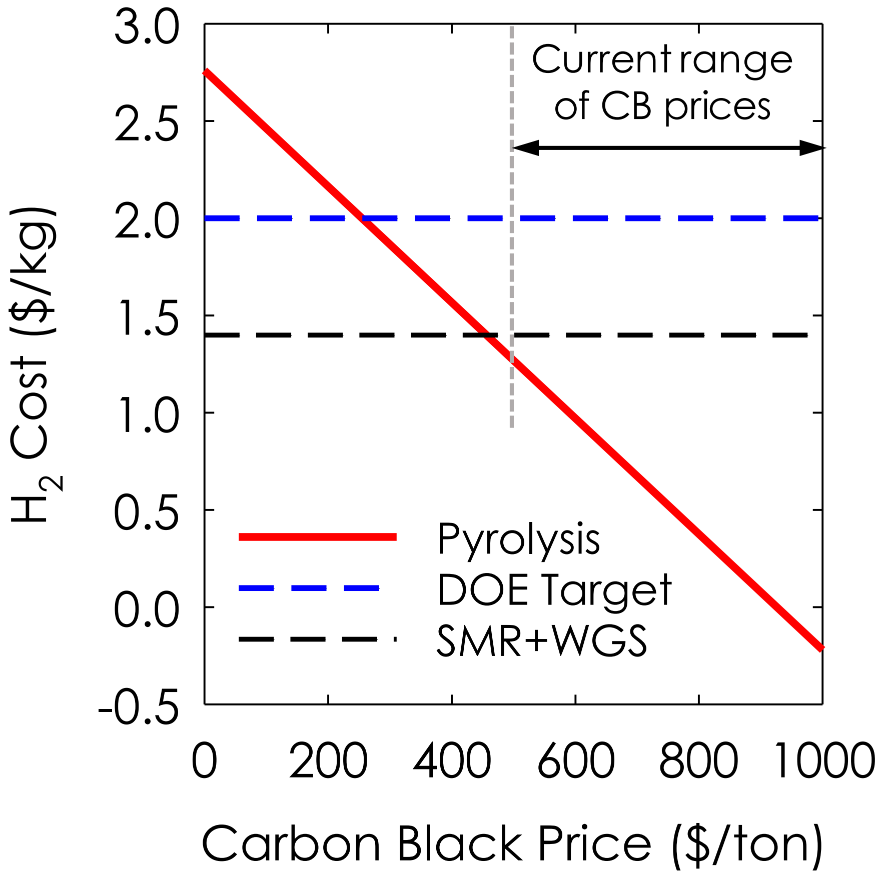
- Lower cost $H_2$ \$0.5-1.50/kg
- No $CO_2$ emissions

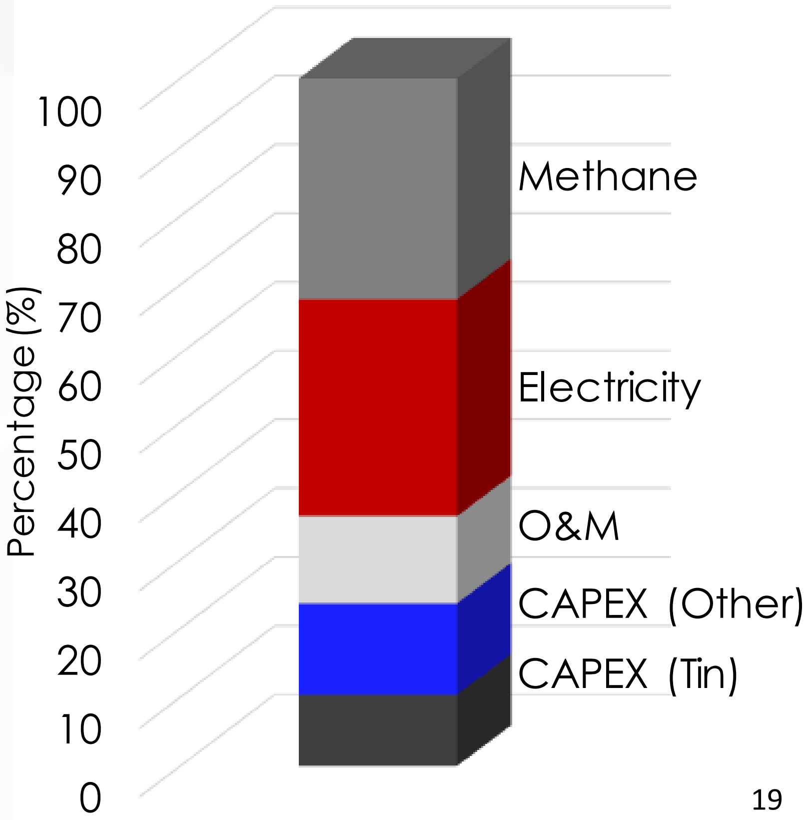
- Produces carbon black
- No corrosion – No plugging!

- We now know how to make it
- We know how to pump Sn(l)



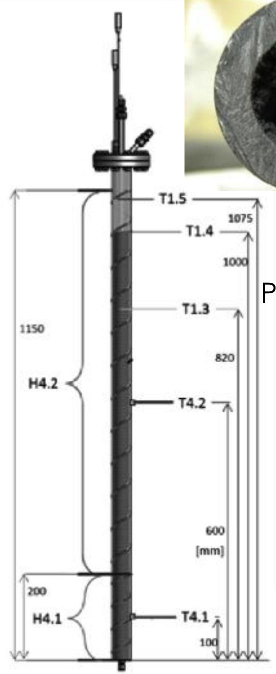
# THE COMPELLING ECONOMICS

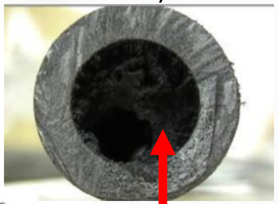


# Prior Work – Laying the Foundation

Wetzel's Group
at KIT in Germany

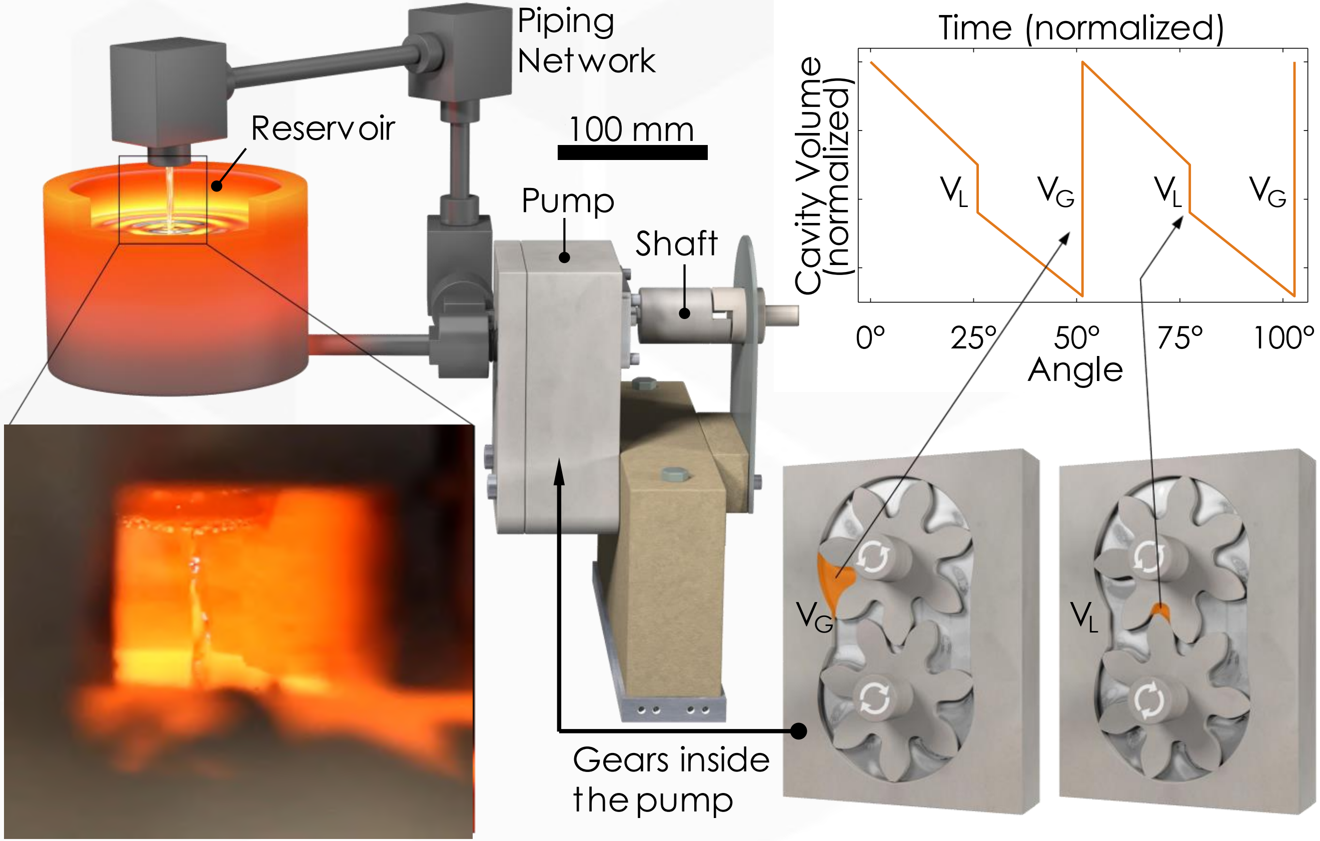


Tin Solves the
Plugging Problem

M. Plevan *et al.* Int. J Hydrogen
Energy, 40, 25, 8020-8033 (2015)

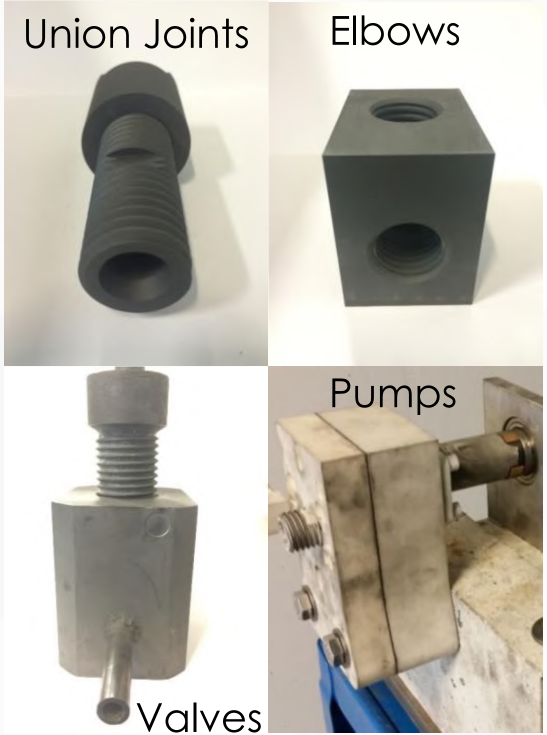
The PI's Group - C. Amy et al., Nature, 550,199–203 (2017)



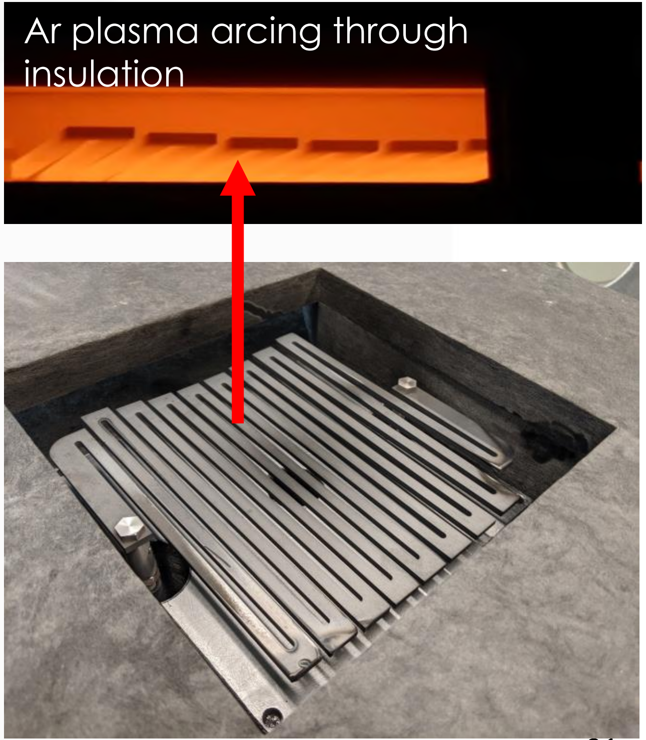
# Prior Work – Laying the Foundation

For T ≤ 500°C

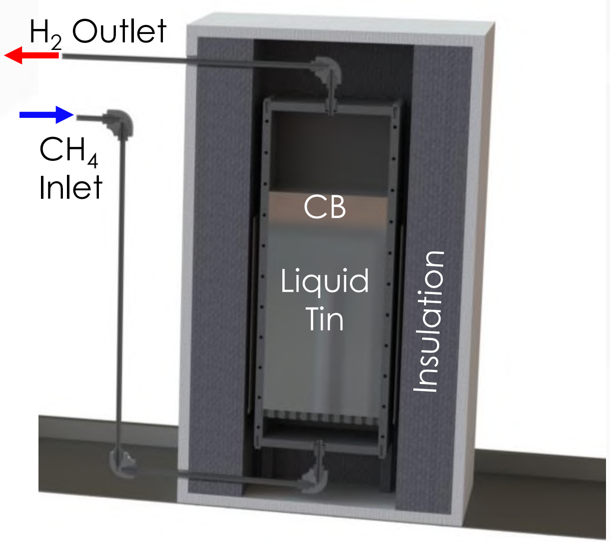

For T ≥ 500°C



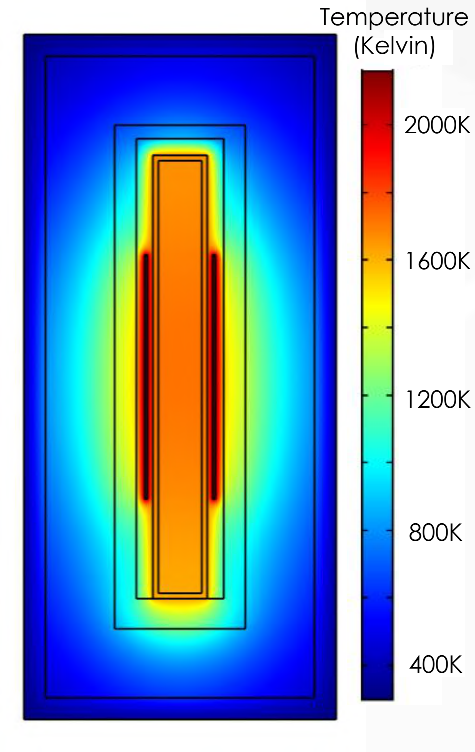

> 2000°C Heaters



# Task 1: Reactor Development



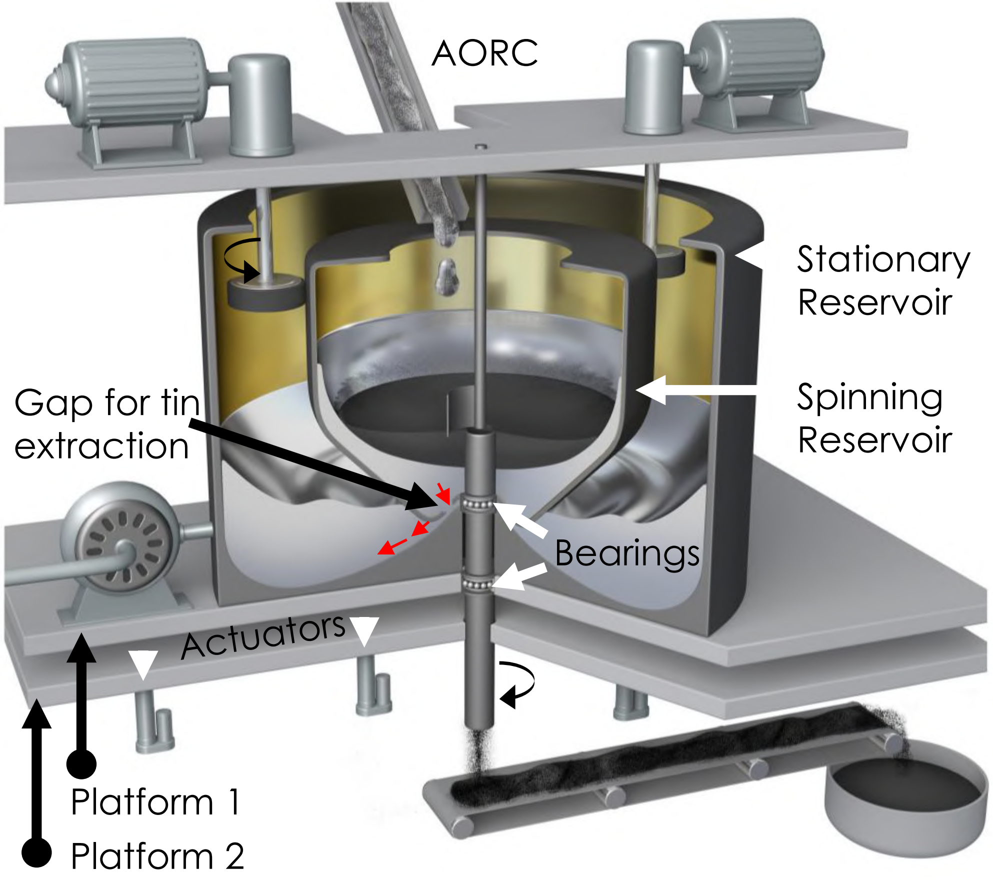

COMSOL Modelling
Guided Experimental Design



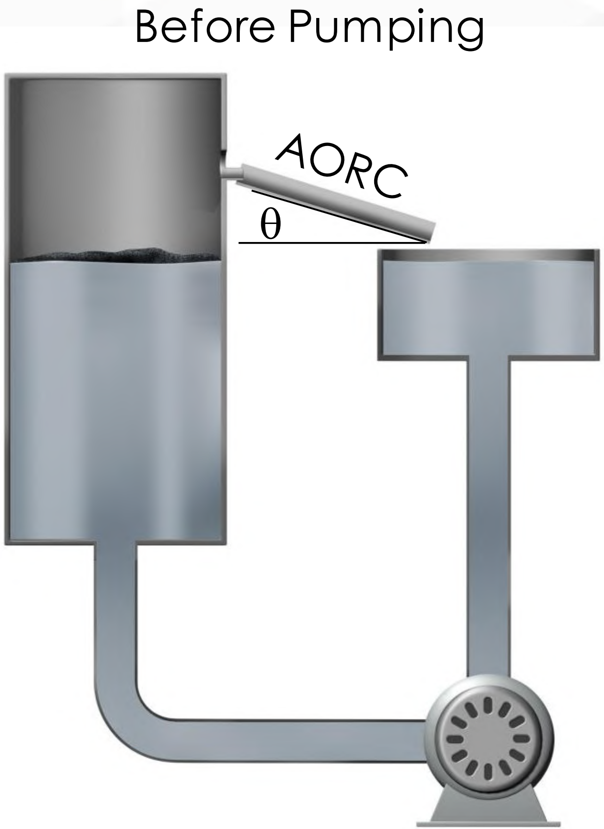

Detailed reactor modeling:

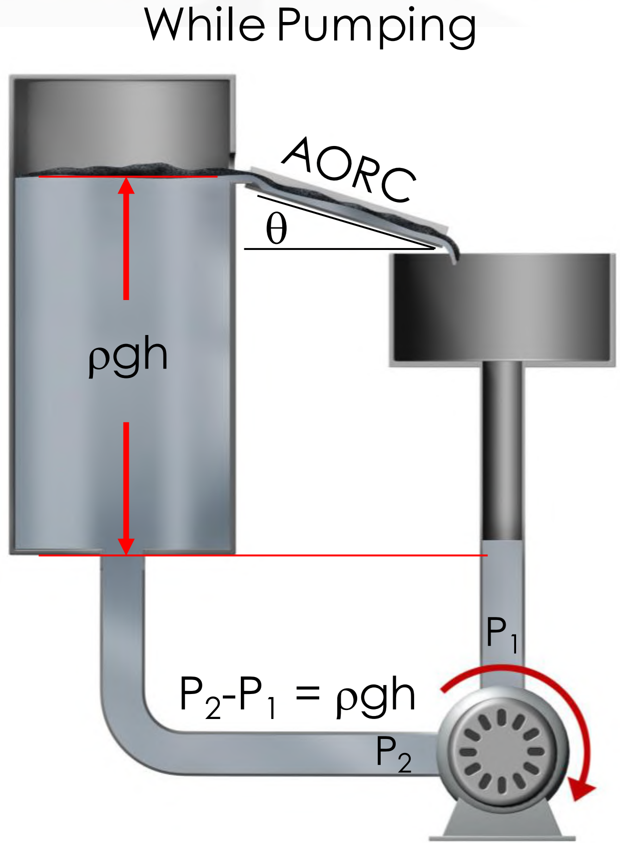
- Predict profiles of temperature, species concentration and bubble size density in reactor
- PDAEs in time, vertical position & bubble size coordinate
- Software: Jacobian (equation-based modeling system) & DAEPACK (numerical engine)
- Incorporate detailed reaction kinetics models for methane pyrolysis via, e.g., CHEMKIN
- Optimization-based experimental design with reactor model for model discrimination and parameter estimation
- Cycle of design, experiments, validation

# Task 2: Centrifuge Development



# Task 3: Continuous Reactor System Development

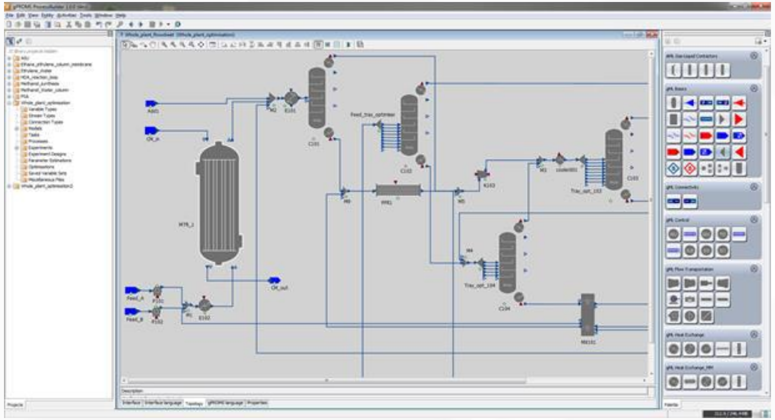


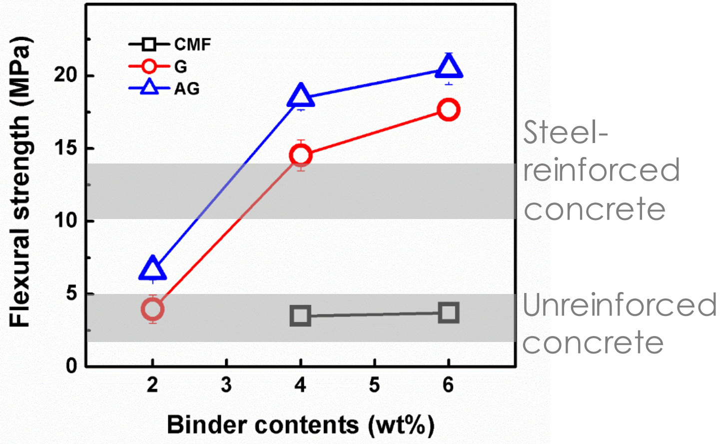
# TASK 4: INDUSTRIAL SCALE SYSTEM MODELING

Liquid Droplet Heat Exchanger Model

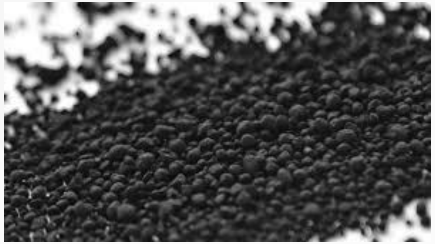
Full System Model for Performance



Yu Qiao (UCSD) Construction Material



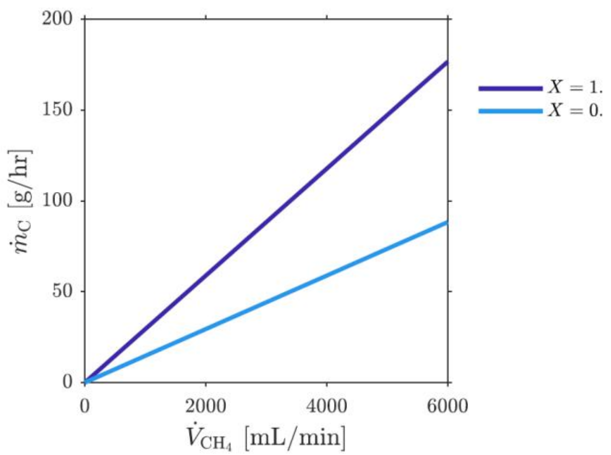

Carbon Black (CB)



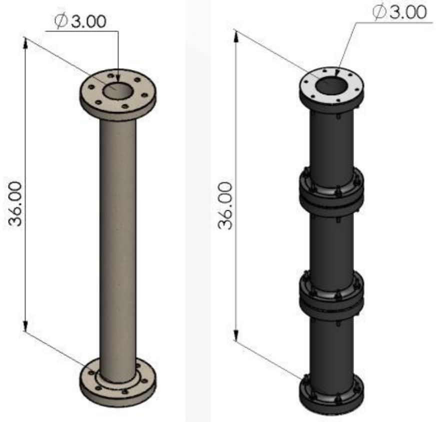
Hydrogen

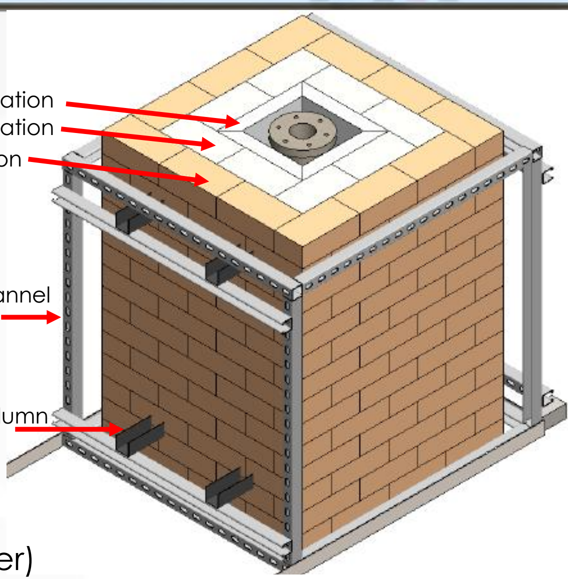

Technoeconomics

# Progress to date



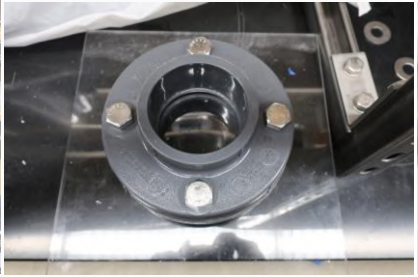

SiC vs. Graphite Reactor?

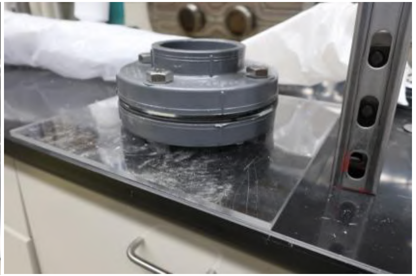


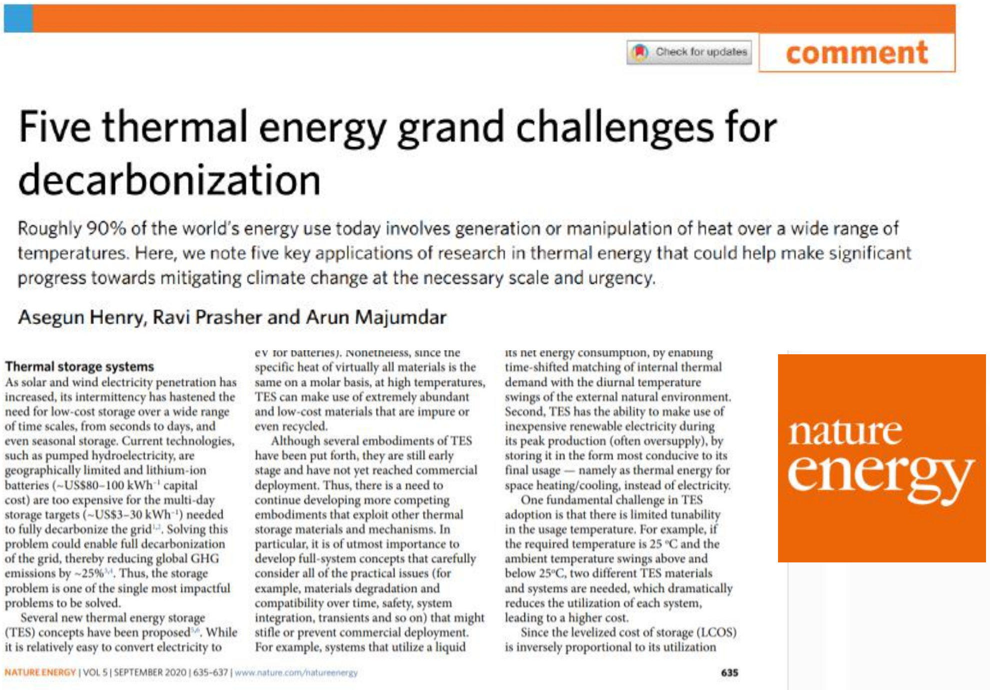


Mock reactor (water)





# Top 5 Problems in Thermal Science & Engineering



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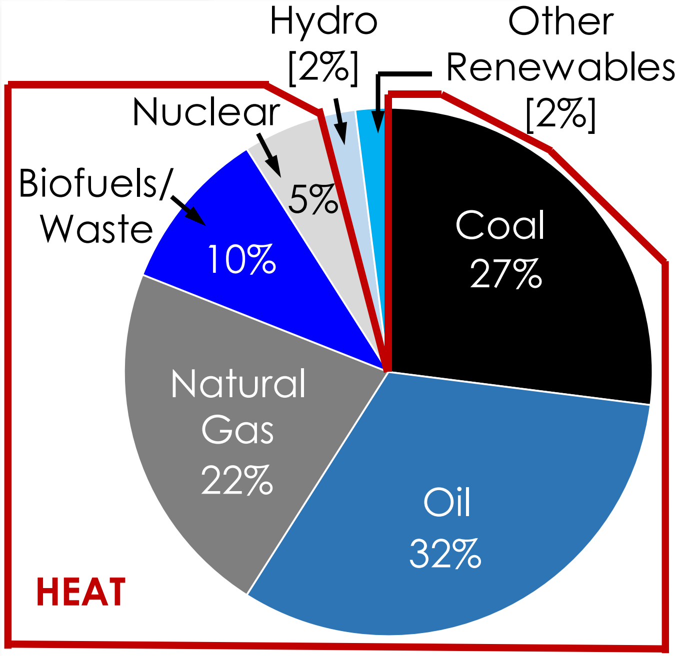
nature energy



A. Henry, R. Prasher, A. Majumdar, Nat Energy 5, 635–637 (2020)

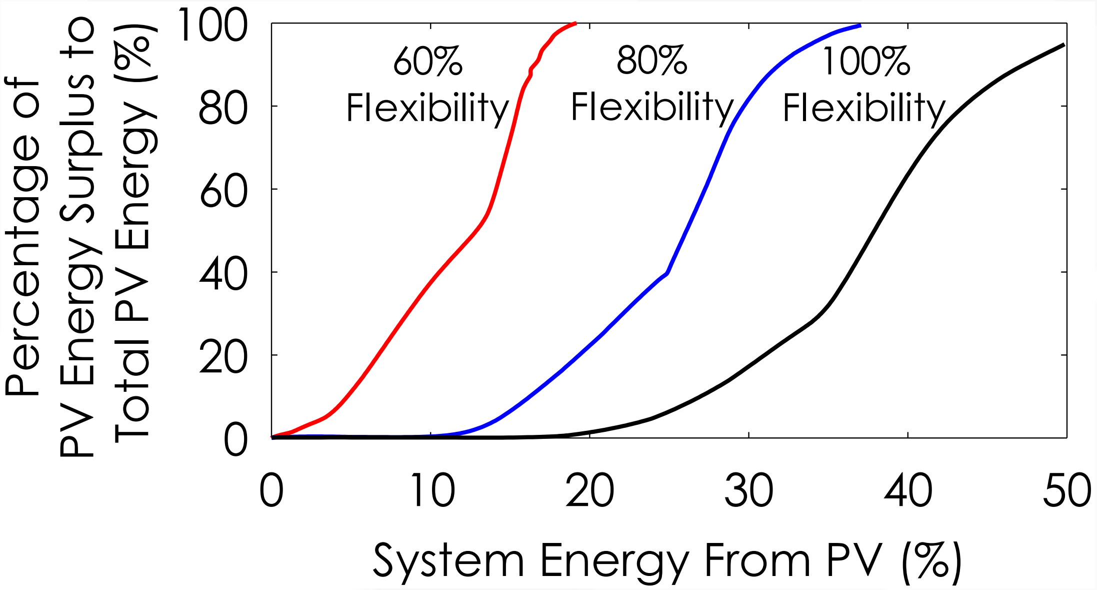


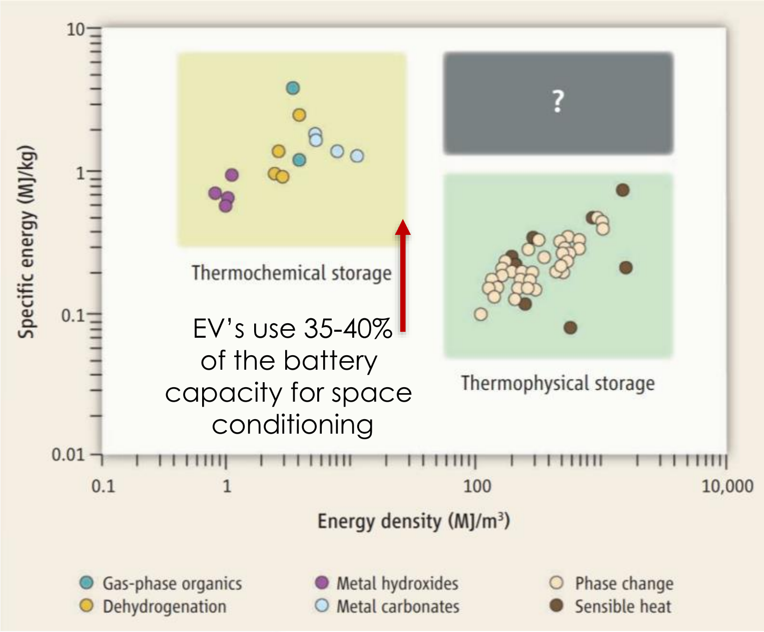

Global primary energy usage in 2016 – IEA Energy Outlook

# High Energy Density Thermal Storage

P. Denholm, R. Margolis, Energy Policy, 35, 2852–2861 (2007)

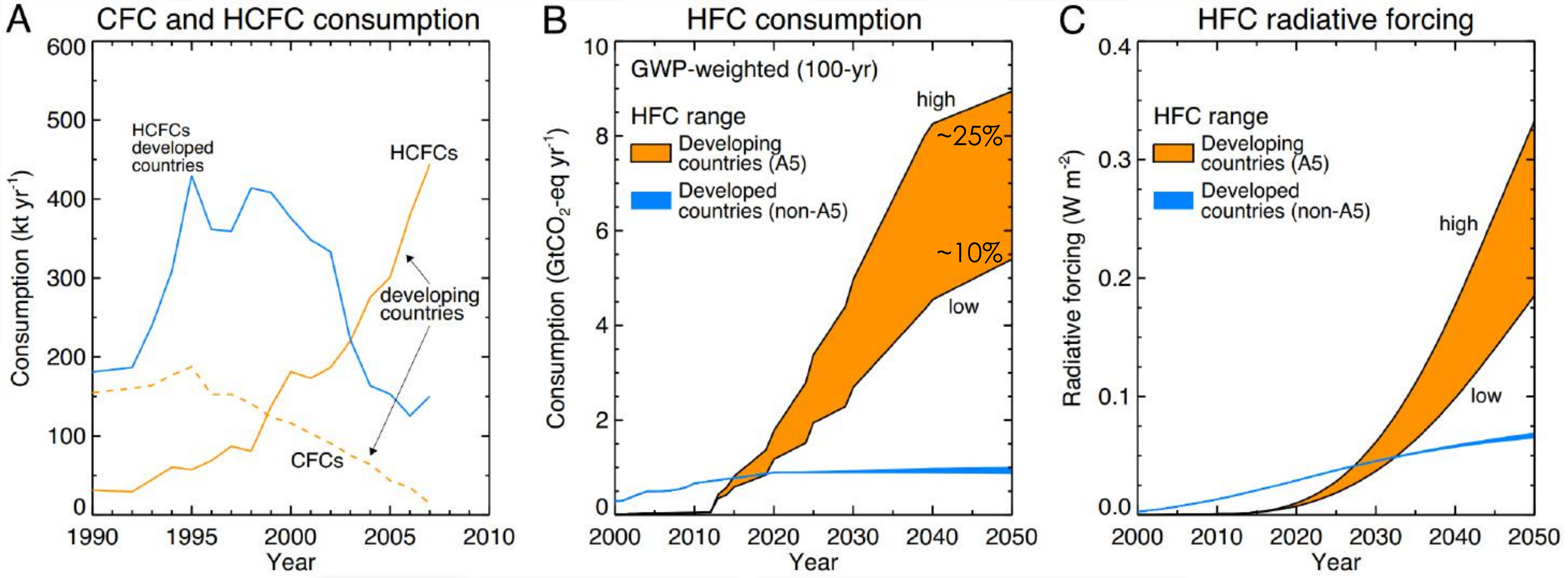
I. Gur *et al.* Science, 435, 1454 (2012)



# Reinventing Cooling

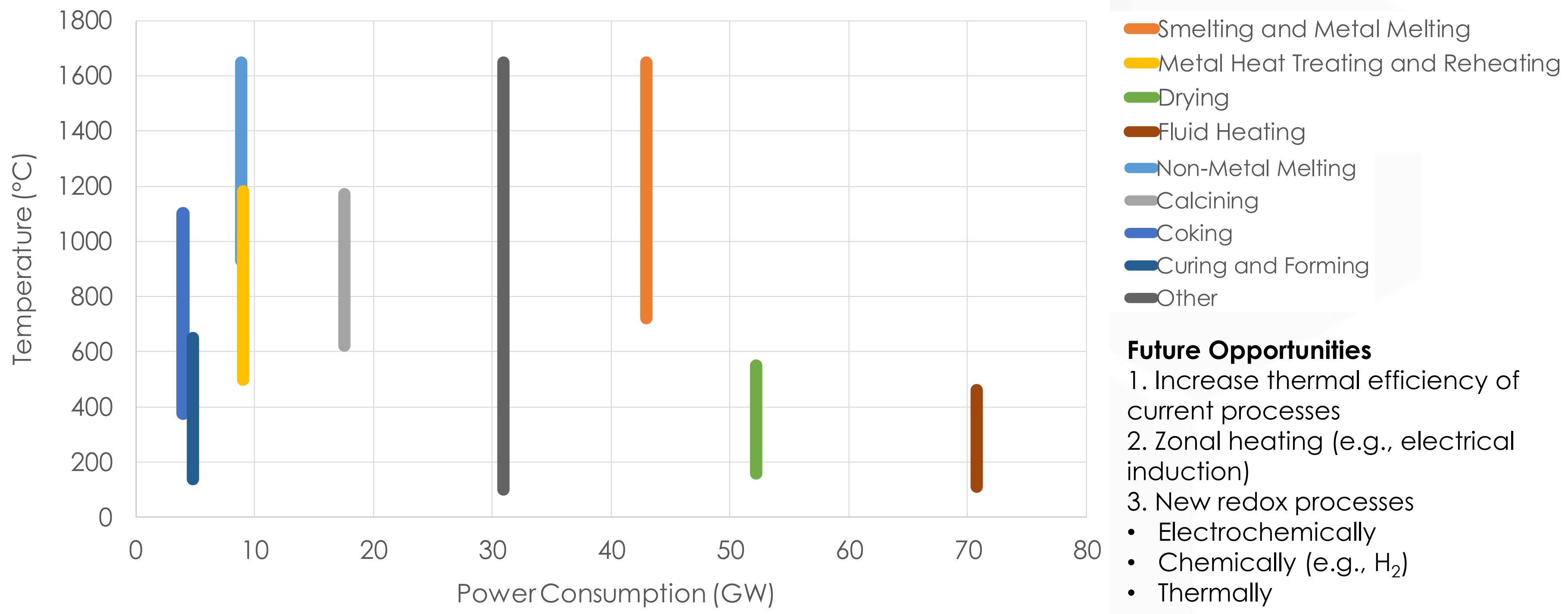
Global CO2 emissions ~ 37 Gt$CO_2$-eq → HFCs could become 10-25% of the problem!




G. Velders et al. PNAS, 106, 27, 10949-10954 (2009)

# Decarbonizing the Industrial Sector

Electricity: 25% Transportation: 14% **Industry: 15%** → Cement: 5% Steel: 4% Aluminum: 1% Hydrogen: 1%

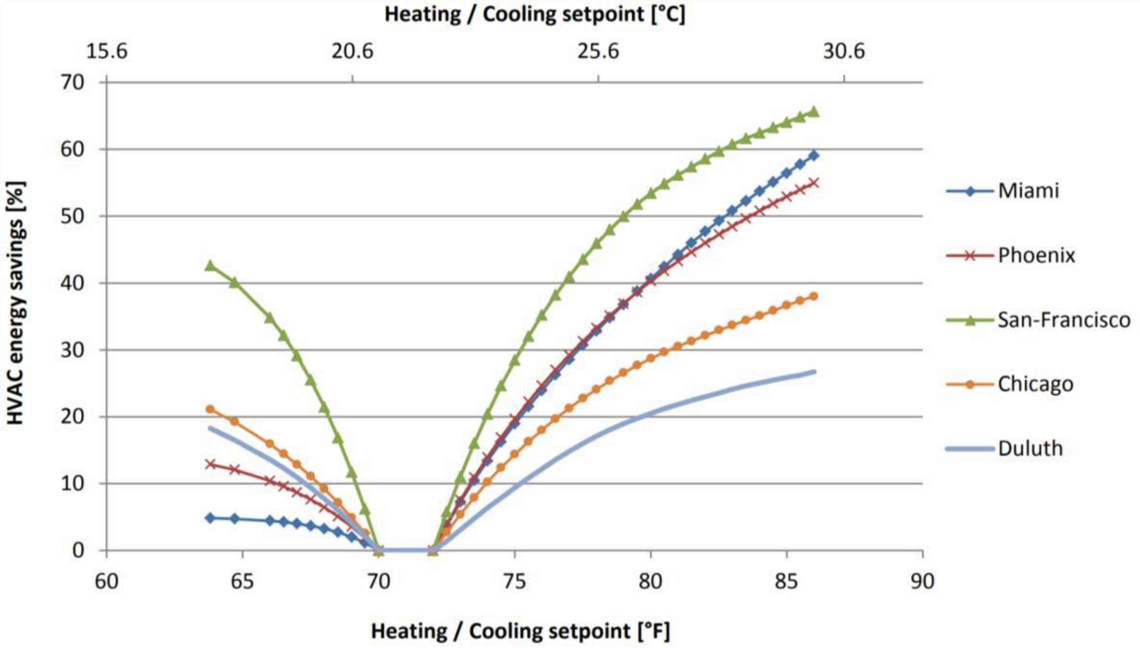



**Future Opportunities**

1. Increase thermal efficiency of current processes
2. Zonal heating (e.g., electrical induction)
3. New redox processes
   - Electrochemically
   - Chemically (e.g., $H_2$)
   - Thermally

# Zonal Heating and Cooling

Space heating and cooling ~ 13% of US energy usage




T. Hoyt *et al.*, Building and Environment, doi:10.1016/j.buildenv.2014.09.010

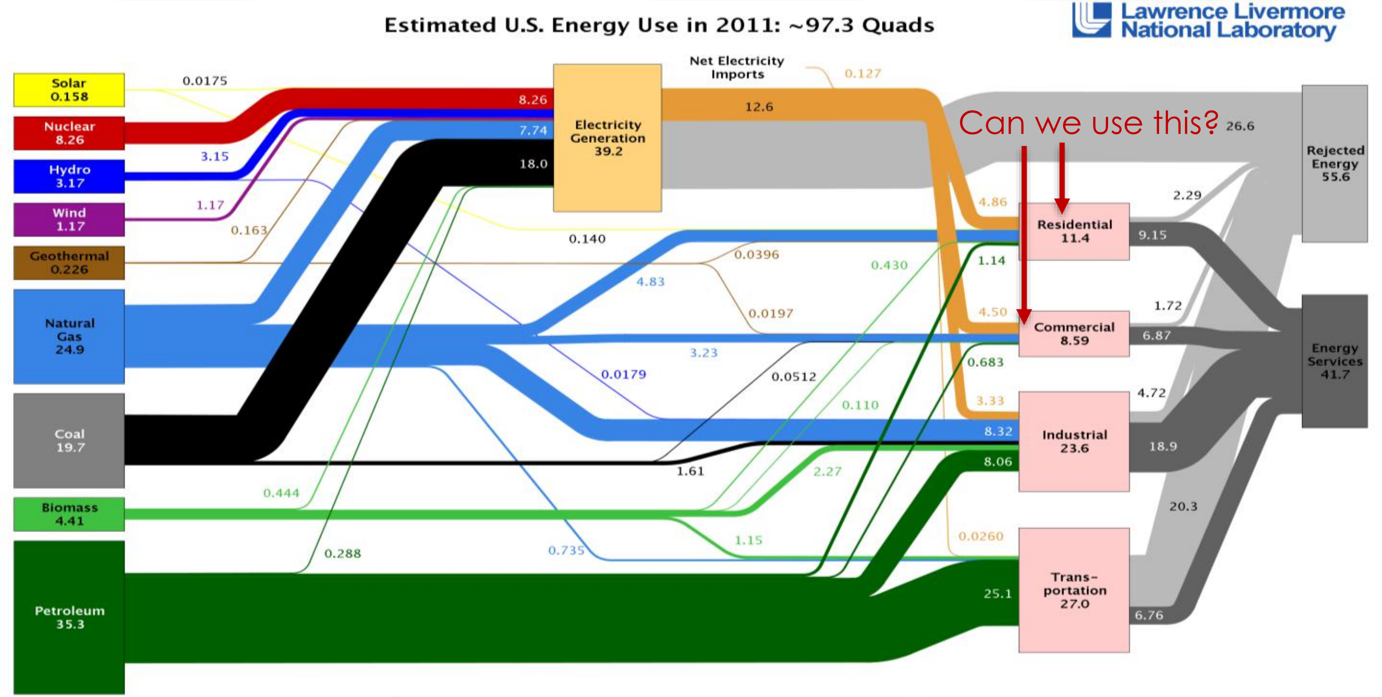
Building


Local

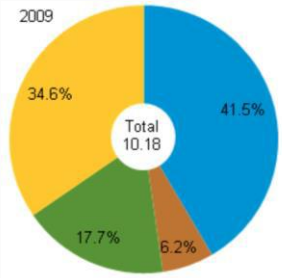
Wearable

# Long Distance Transmission of Heat

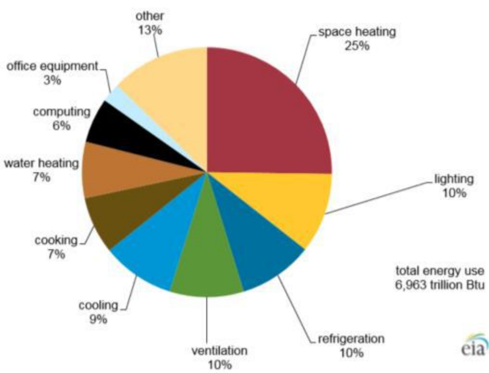
building energy goes to heating at < 60°C
~ 60% for residential
~ 32% for commercial




## Residential




## Commercial



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- Andrew Rohskopf
- Spencer Wyant
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High Temperature
Energy Systems

- Alina LaPotin
- Colin Kelsall
- Dr. Mehdi Pishahang
- Dr. Qingzi Zhu

Selected Collaborators:

- Ken Sandhage (Purdue)
- Paul Barton (MIT)
- Samuel Graham (GT)

Former Group Members:

- Dr. Diane England
- Dr. Cansheng Yuan
- Dr. Caleb Amy
- Dr. Wei Lv
- Dr. Hamid Seyf
- Dr. Freddy DeAngelis
- Dr. Murali Muraleedharan
- Dr. Xu Tan
- Dr. Bamdad Barari
- Colby Jarrett
- Greg Wilk
- Malavika Bagepalli
- Daniel Budenstein
- Sanzida Sultana

NSF

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CHANGING WHAT'S POSSIBLE

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# QUESTIONS?