Multi-Input Hybrid Heat Exchangers

next-gen decarbonization with current-gen renewable technologies

Industrial Energy Use: Massive

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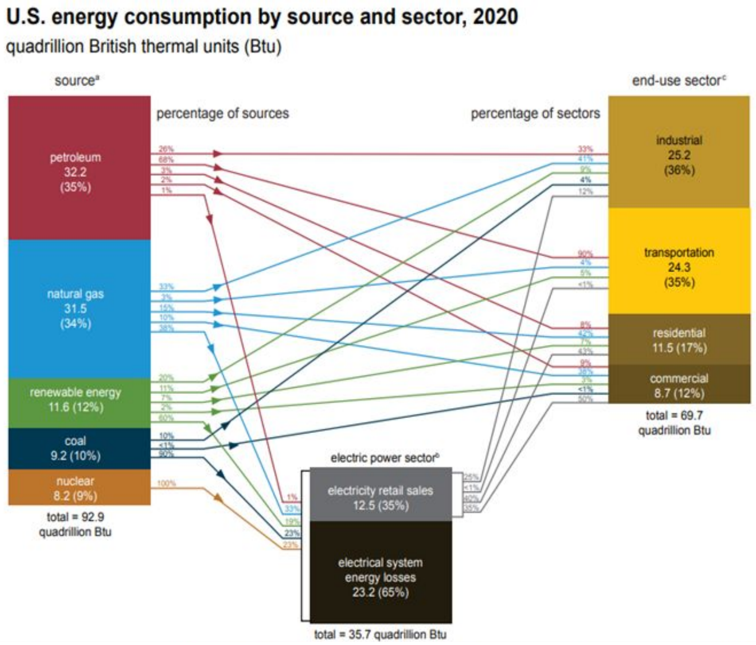
  - US: ~25 quads/yr



US EIA *Monthly Energy Review*, **2021**.

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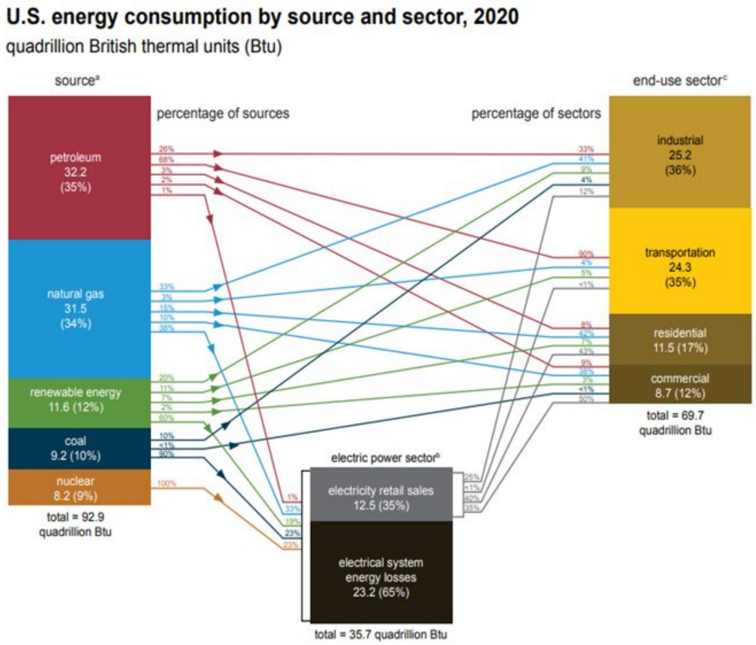

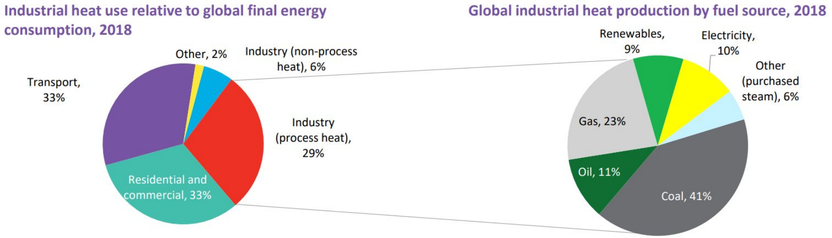

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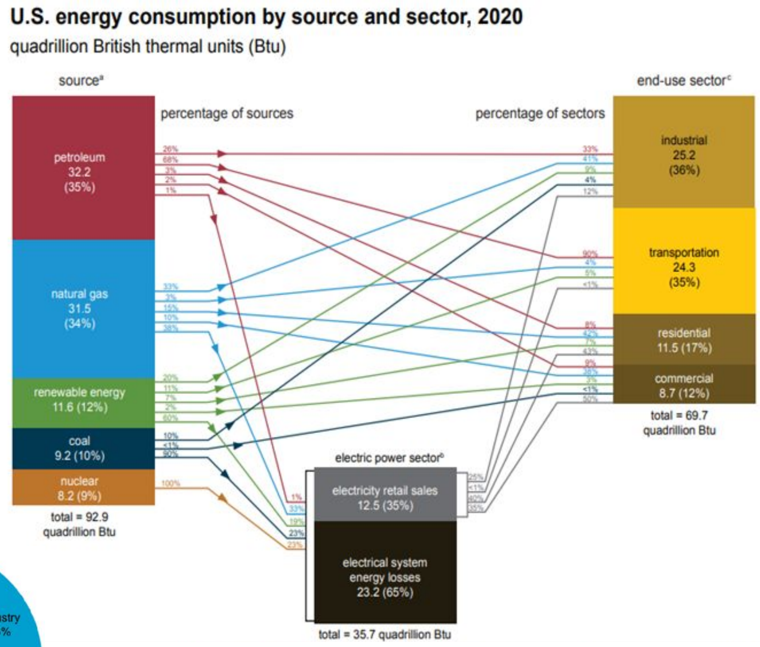

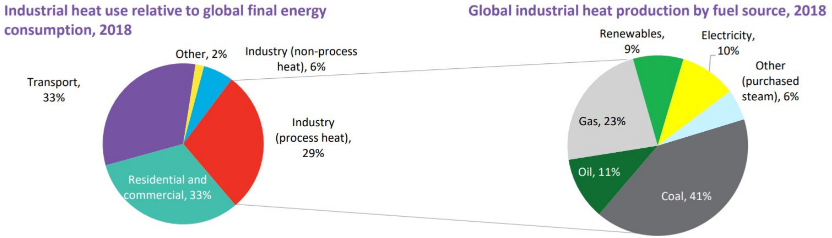

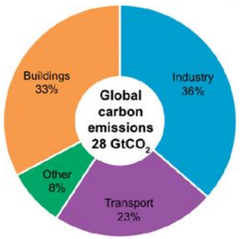

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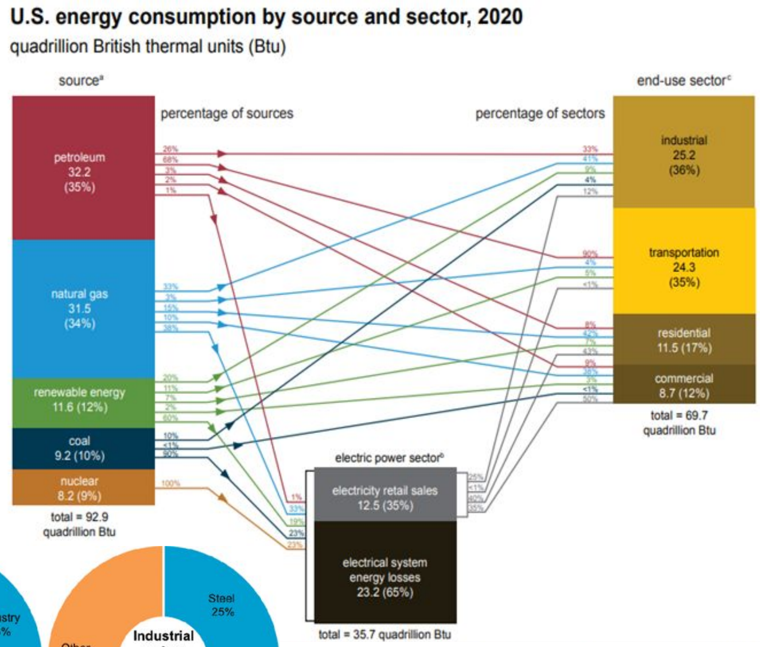

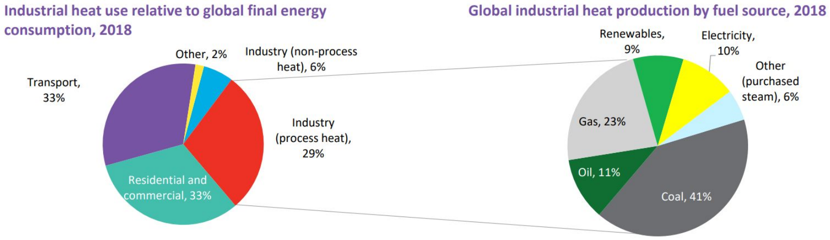

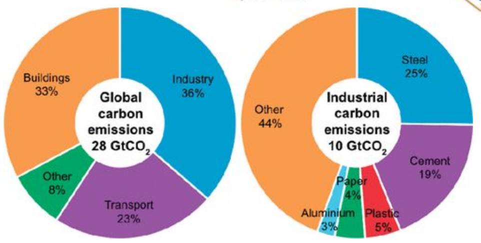

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High T Complicates Decarbonization

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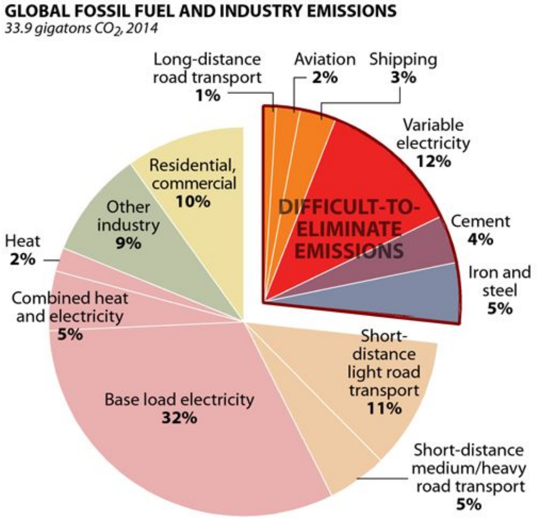

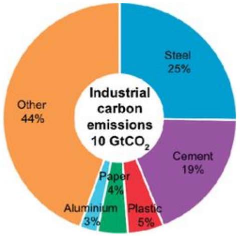

Science **2018**, *360* (6396), eaas9793

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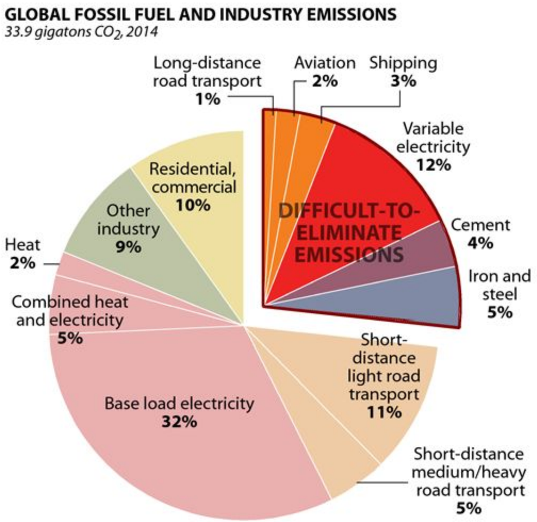

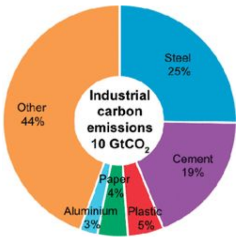

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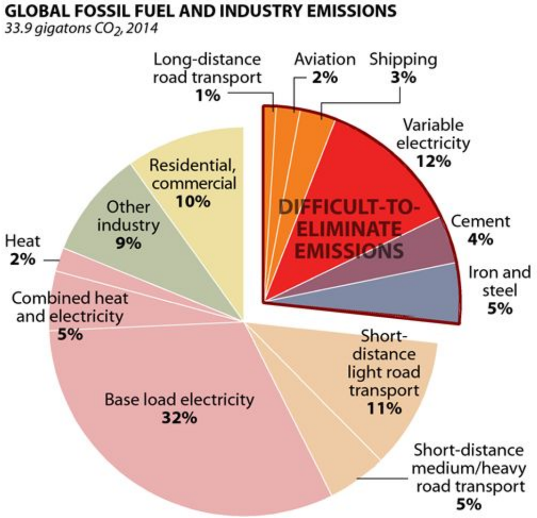

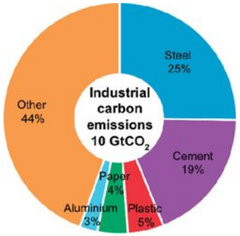

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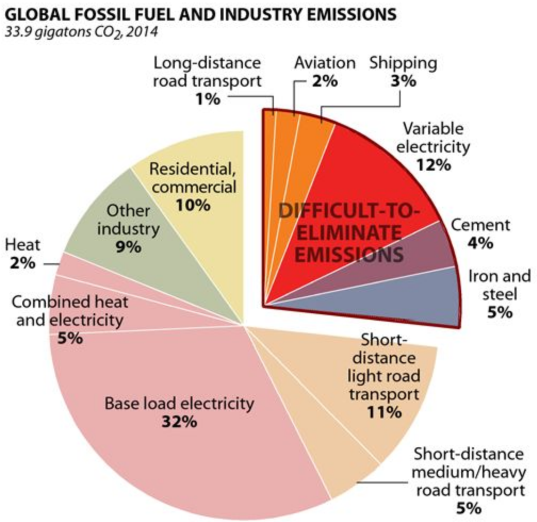

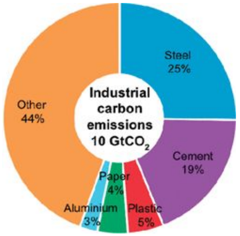

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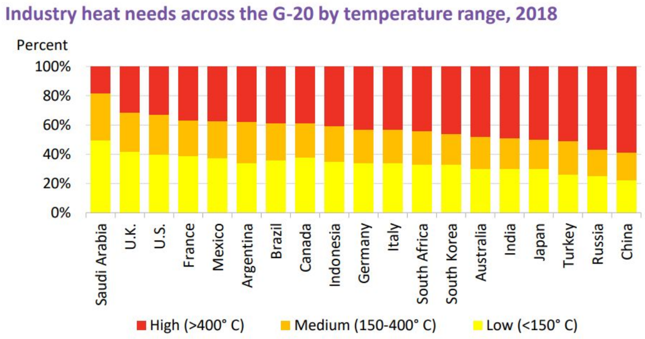

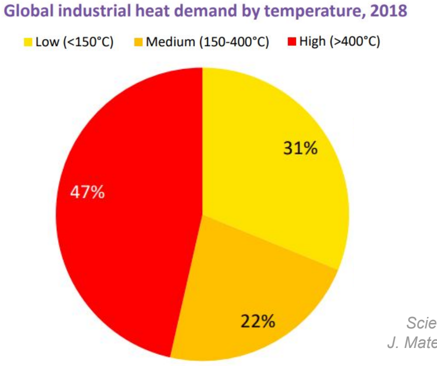

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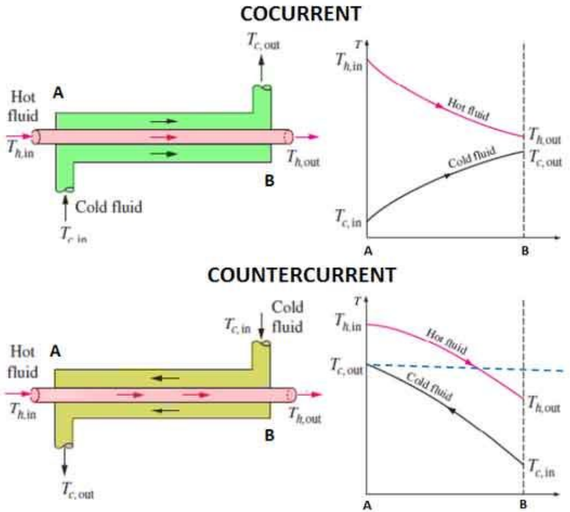

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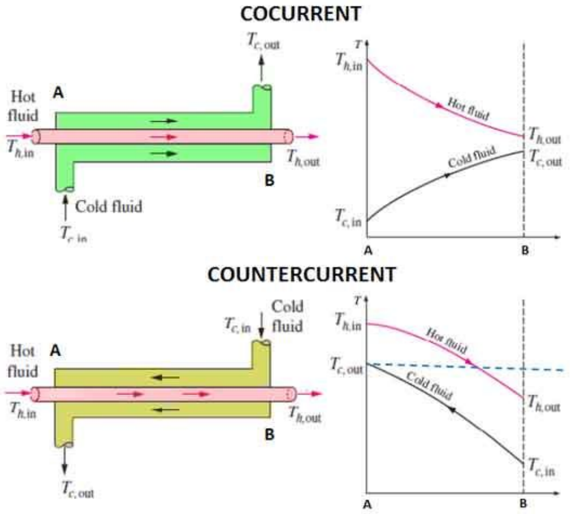

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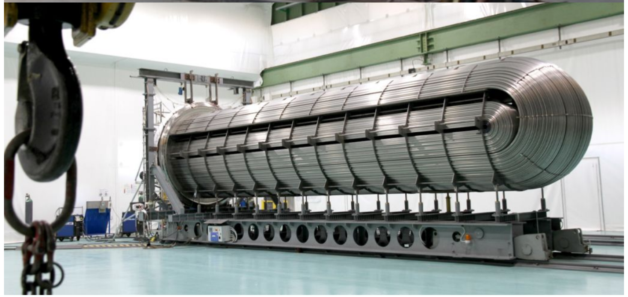

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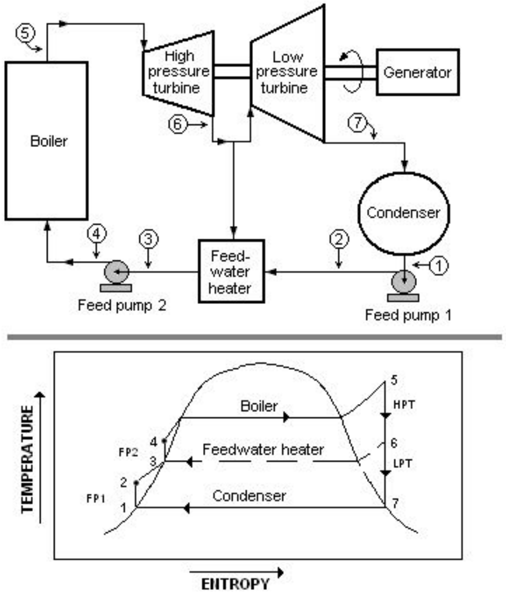
  - HX systems are massive! (**$$$**)
  - True for HXers and boilers



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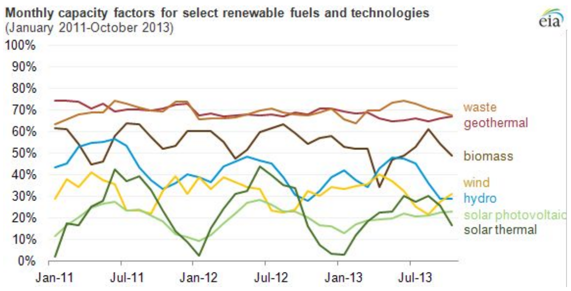

Renew. Sust. Energ. Rev. **2018**, *89*, 51.

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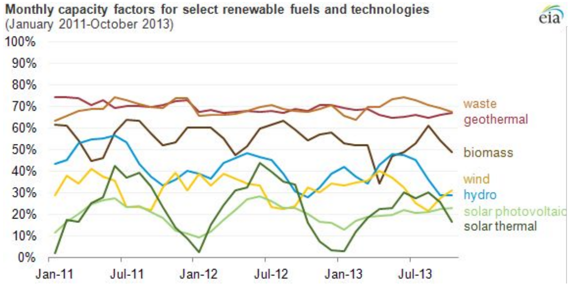

Type of power generation	Capacity factor (%)
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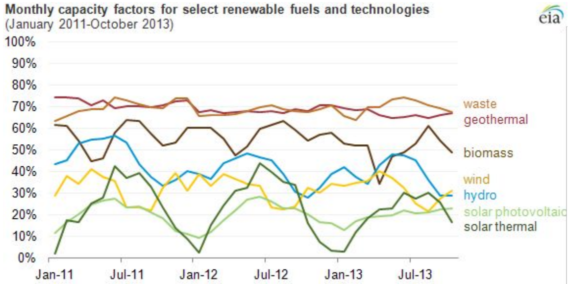

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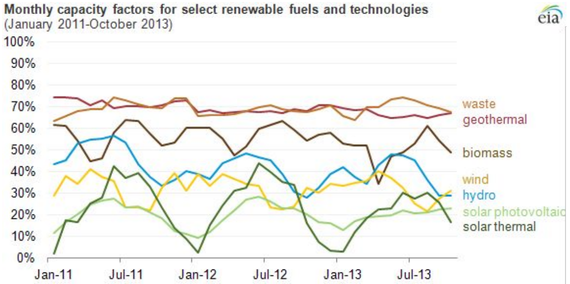

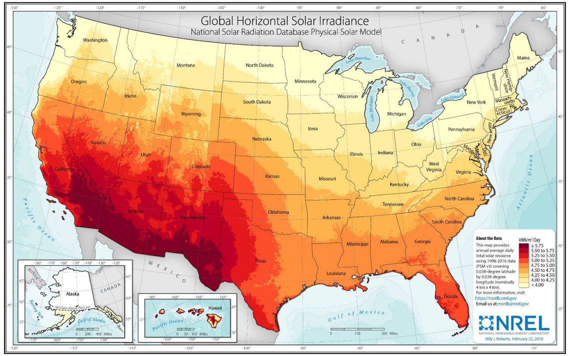

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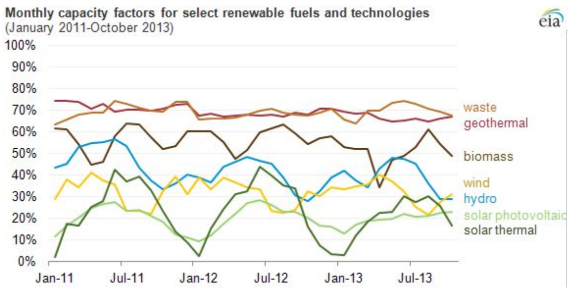

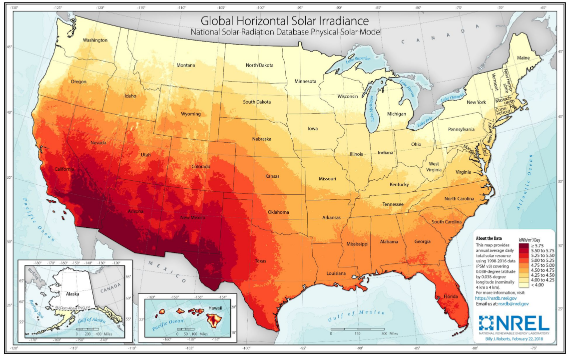

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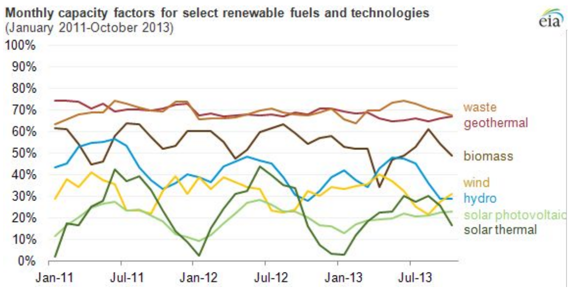

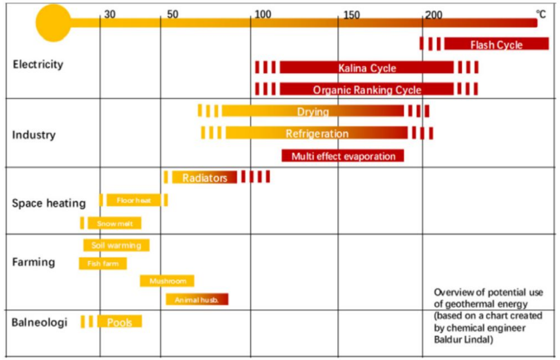

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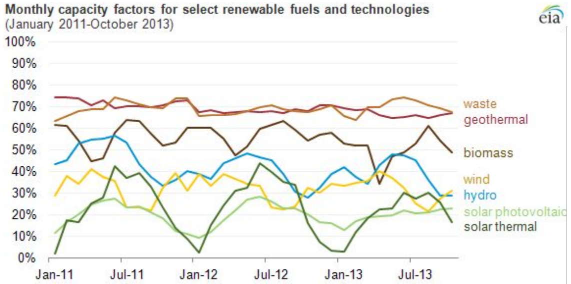

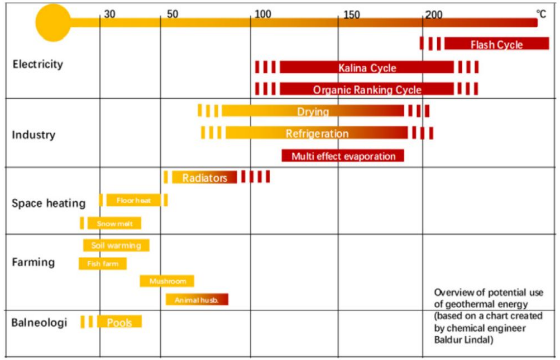

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Energy **2007**, *32*, 1698.

Inspiration: Hybrid Geothermal/CSP

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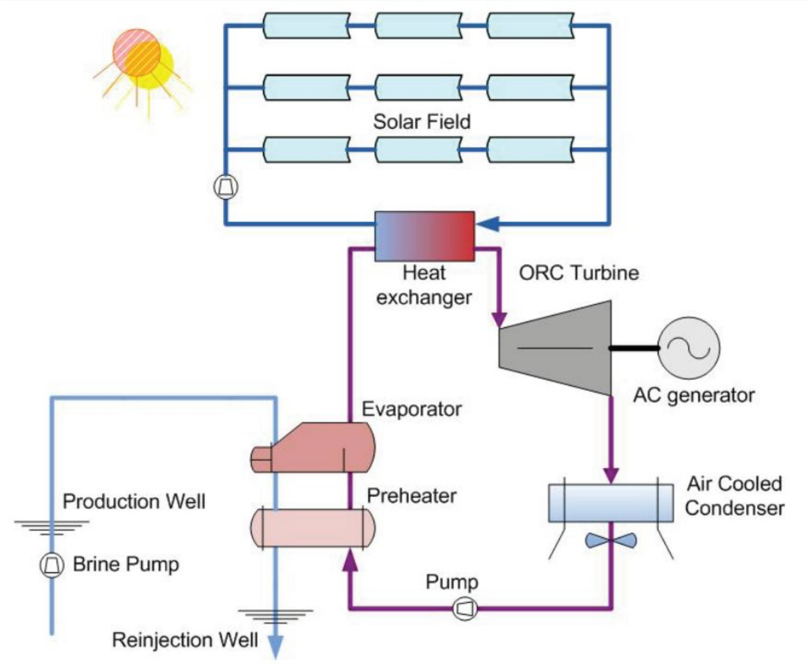
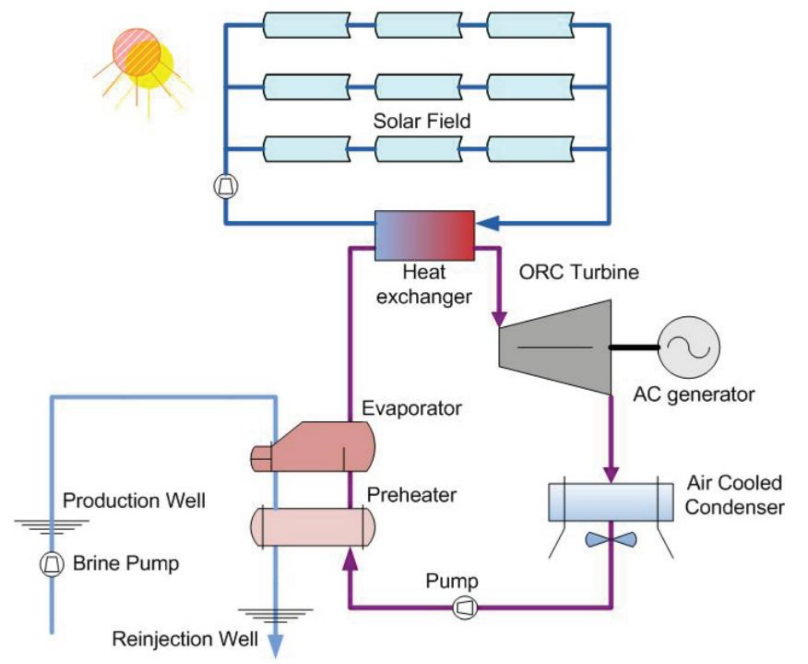


J. Clean. Prod. **2020**, *250*, 119481.

Inspiration: Hybrid Geothermal/CSP

- Hybrid systems cover each others' flaws



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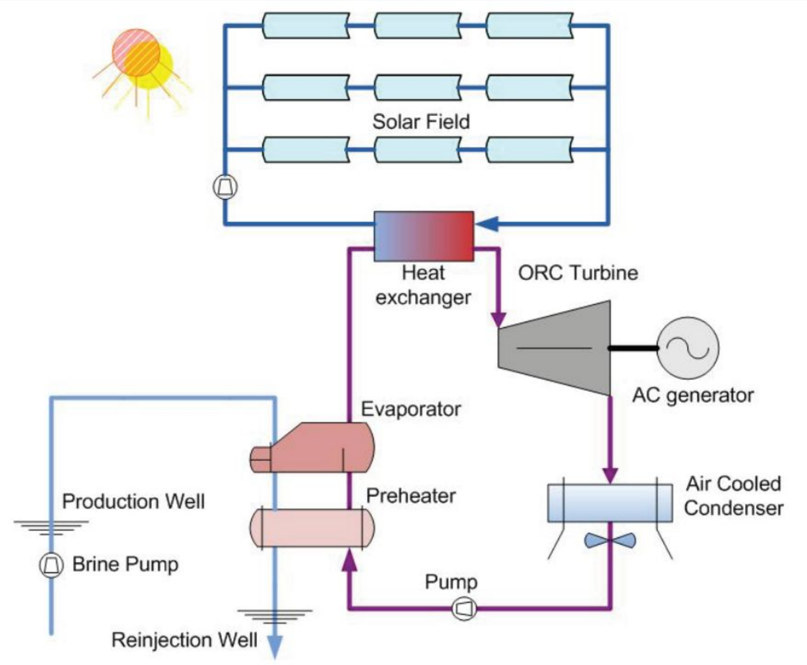

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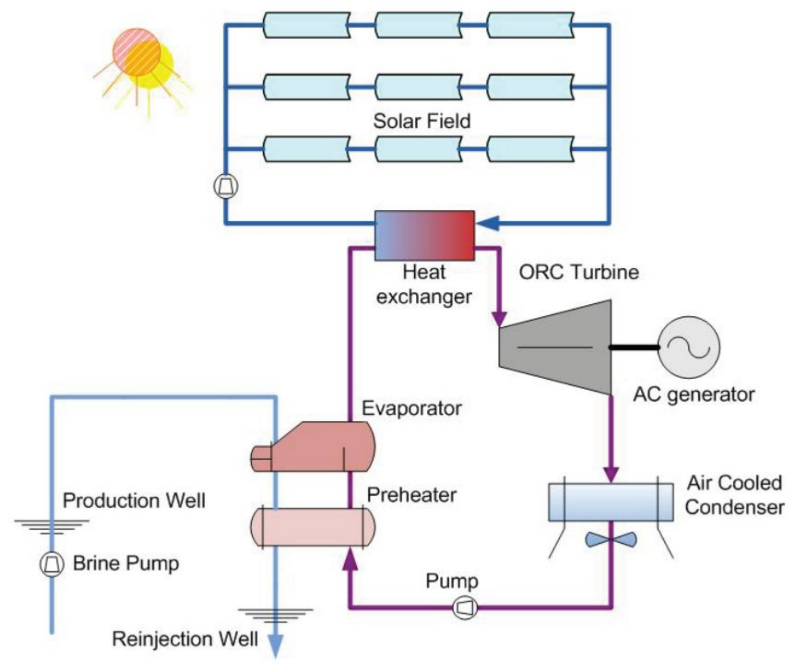

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J. Geophys. Res. Solid Earth **2019**, *10*, 2115.
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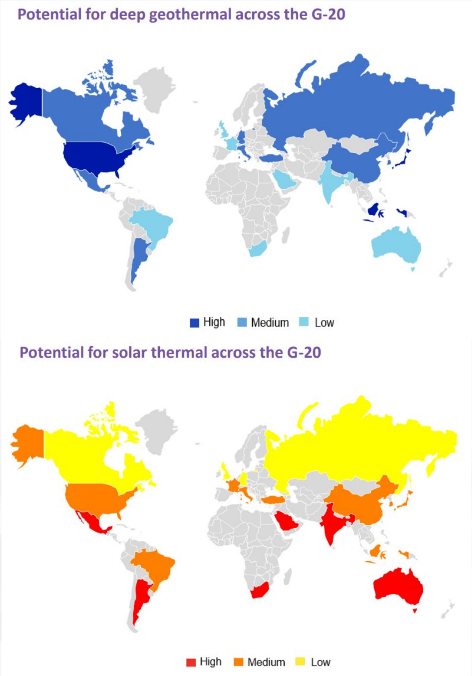
Inspiration: Hybrid Geothermal/CSP

- Hybrid systems cover each others' flaws
  - Geothermal fluid provides TES for CSP
  - CSP augments T of geothermal fluid
  - Also exacerbates common shortcomings!



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Hybrid Energy Systems

Joule **2021**, *5* (1), 47.

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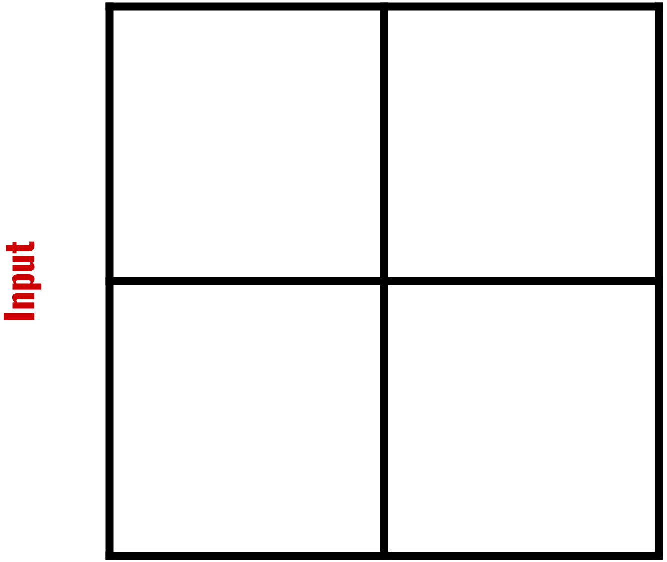

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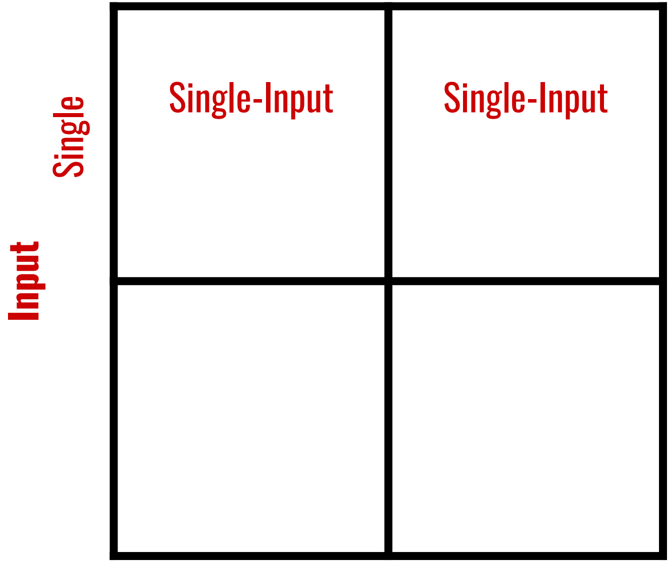

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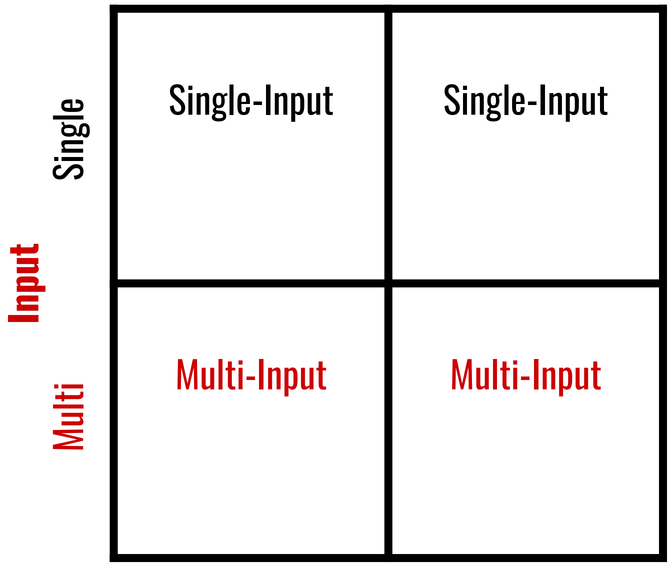

Joule **2021**, *5* (1), 47.

Hybrid Energy Systems

	Output	
Input		
Single	Single-Input	Single-Input
Multi	Multi-Input	Multi-Input

Joule **2021**, *5* (1), 47.

Hybrid Energy Systems

Output

Input	Single	
Single	Single-Input Single-Output **(SISO)**	Single-Input
Multi	Multi-Input Single-Output **(MISO)**	Multi-Input

Joule **2021**, *5* (1), 47.

Hybrid Energy Systems

Input \ Output	Single	Multi
Single	Single-Input Single-Output **(SISO)**	Single-Input Multi-Output **(SIMO)**
Multi	Multi-Input Single-Output **(MISO)**	Multi-Input Multi-Output **(MIMO)**

Joule **2021**, *5* (1), 47.

Hybrid Energy Systems

		Output	
		Single	Multi
Input	Single	Single-Input Single-Output **(SISO)**	Single-Input Multi-Output **(SIMO)**
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Hybrid Energy Systems

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Single	Single-Input Single-Output **(SISO)**	Single-Input Multi-Output **(SIMO)**
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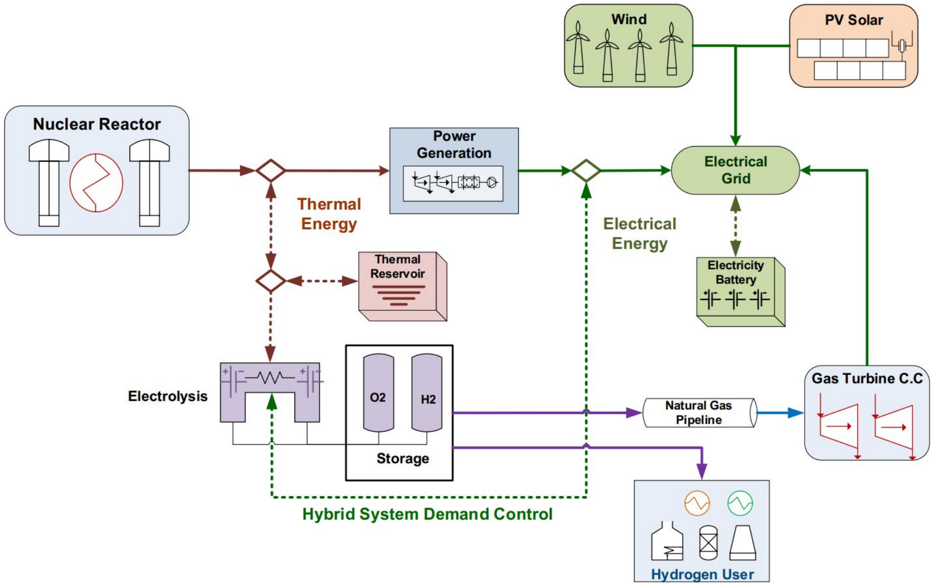

Joule **2021**, *5* (1), 47.
INL/EXT-19-55395-Rev000; Idaho National Lab, **2019**.

Hybrid Energy Systems

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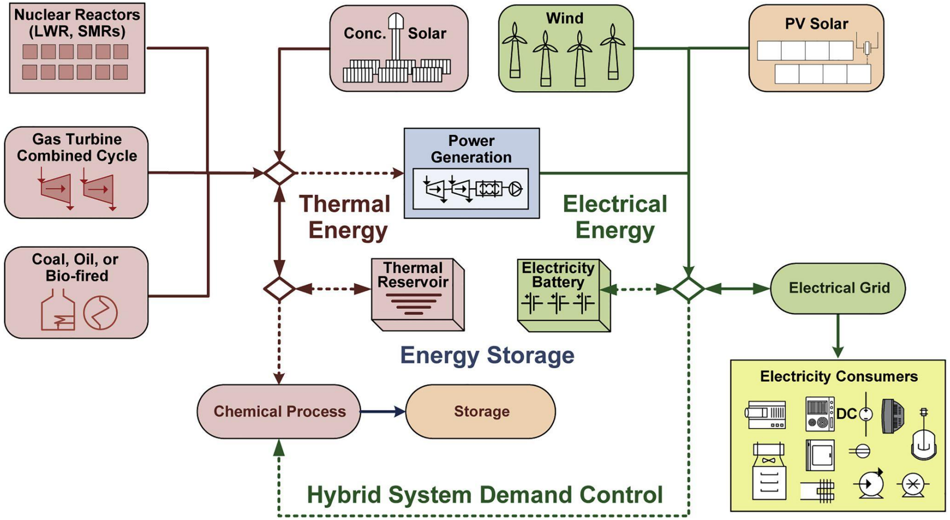

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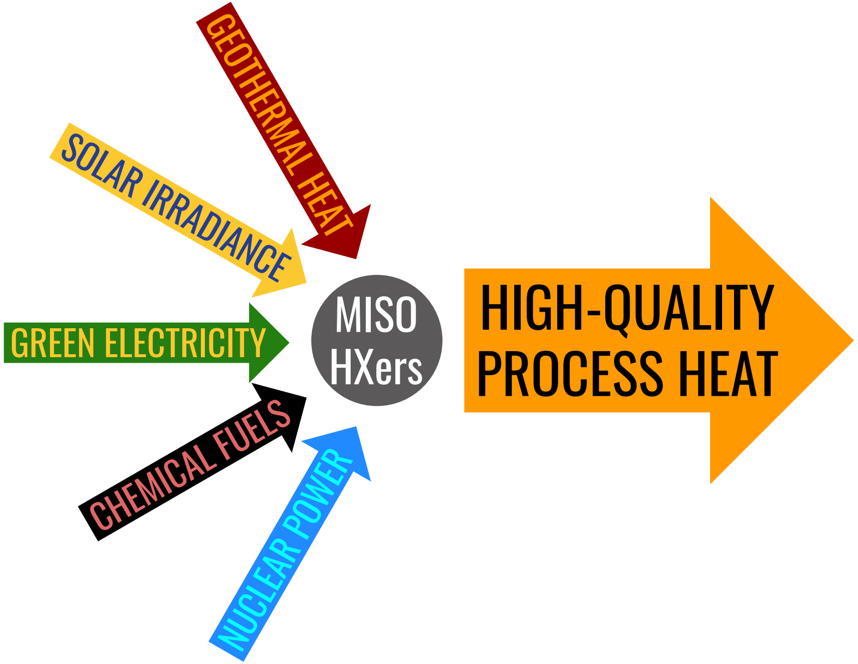

Joule **2021**, *5* (1), 47.
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Hybrid CSP/Biomass Boilers

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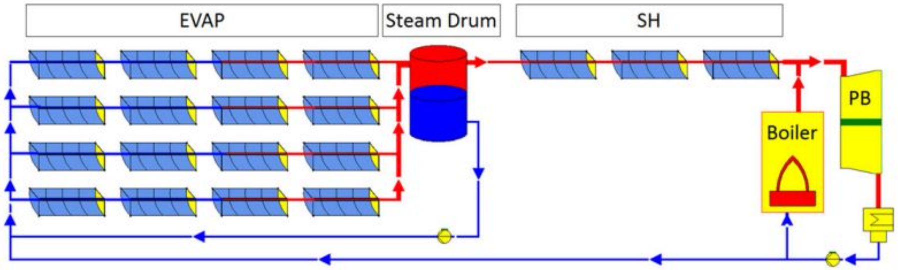
- 60 kW_e scale prototype



Int. J. Low-Carbon Technol. **2018**, *13*, 380.

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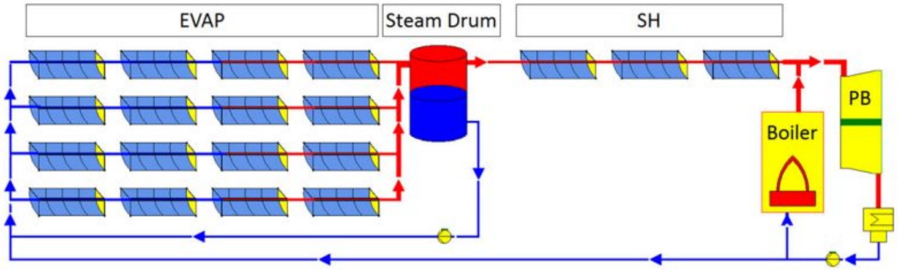

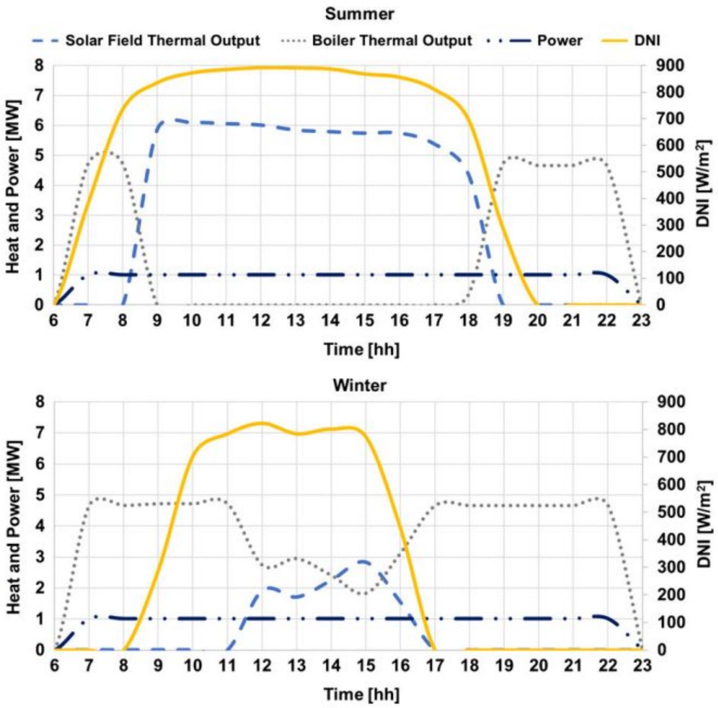

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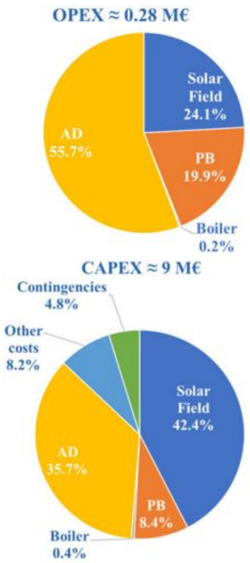

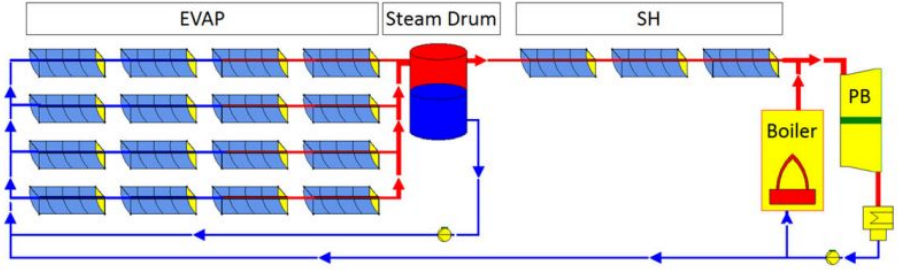

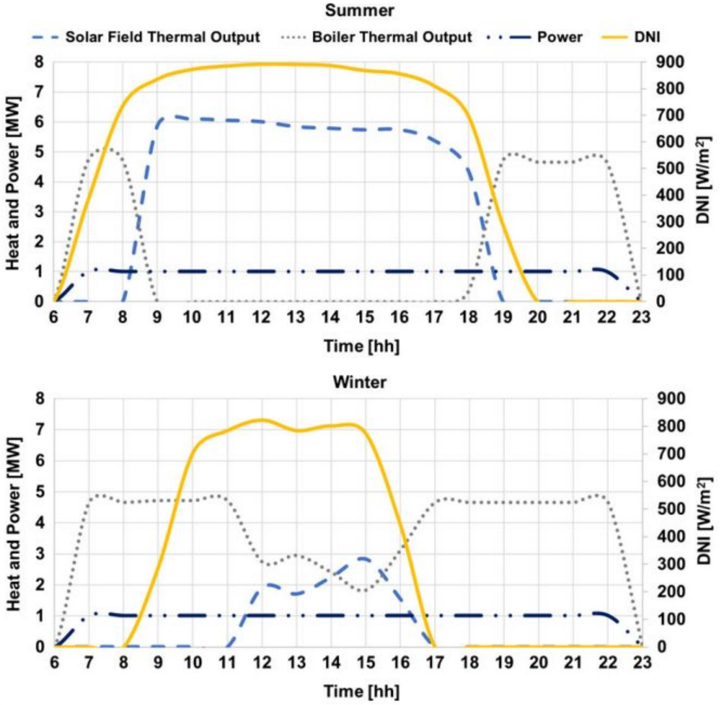

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Hybrid CSP/Biomass Boilers

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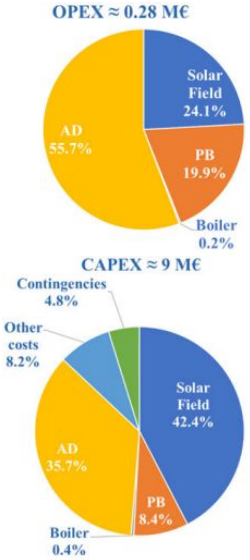
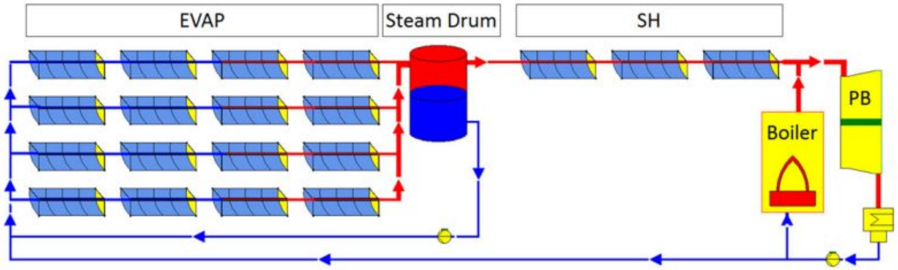
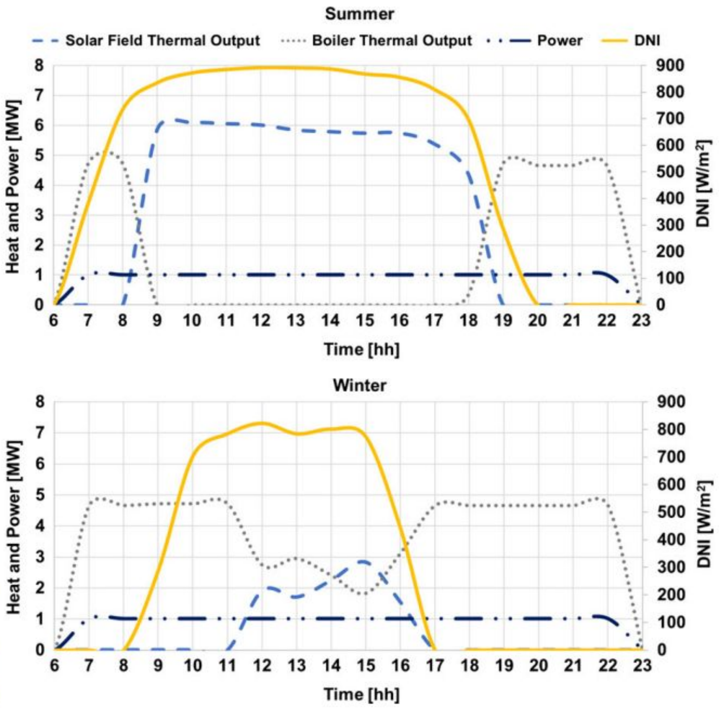
  - LCOE:
    - 14 ¢/kWh_{th}, 19 ¢/kWh_e



$$LCoE_{CHP} = \frac{CAPEX \times CRF + OPEX}{E} - \frac{H}{E} * H_{price} \qquad CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$$





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Opportunity Space:

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How many energy inputs can we cram into a single system?

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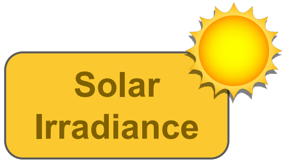

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Solar Irradiance

Chemical Fuels

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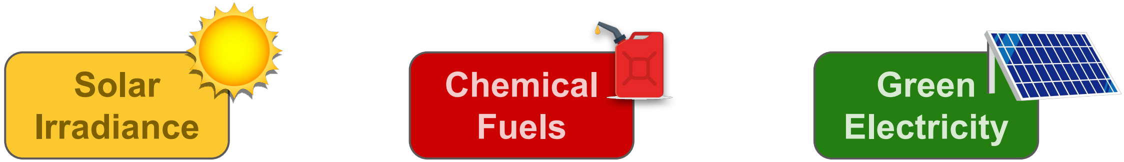

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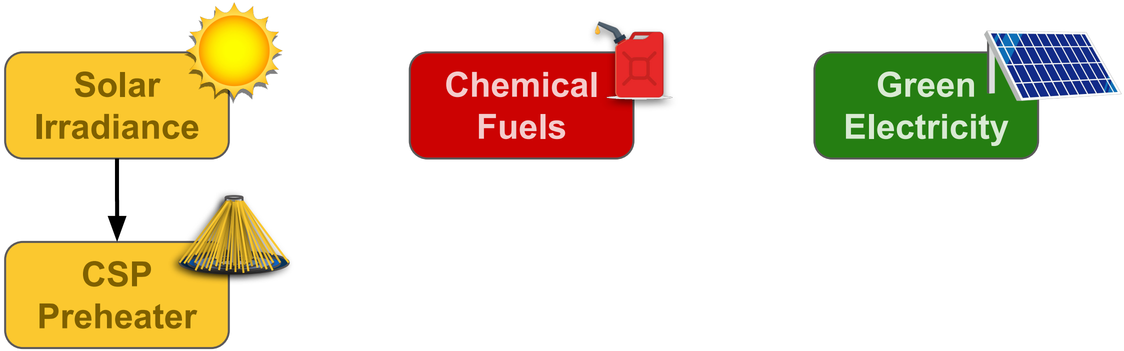

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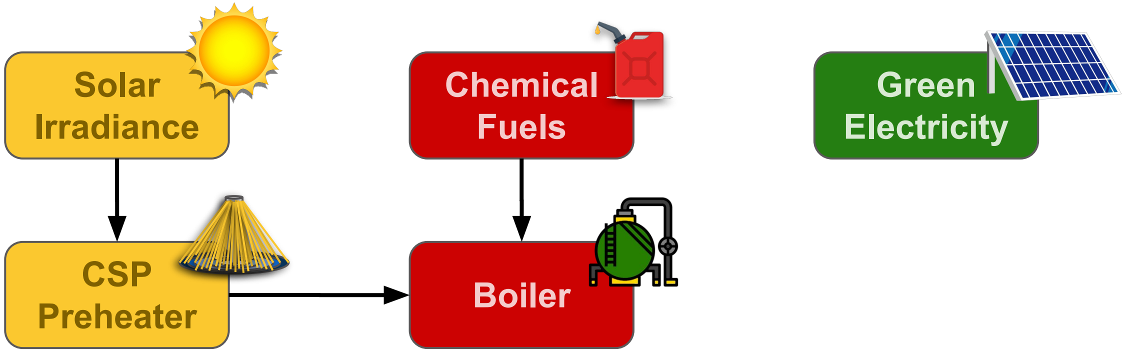

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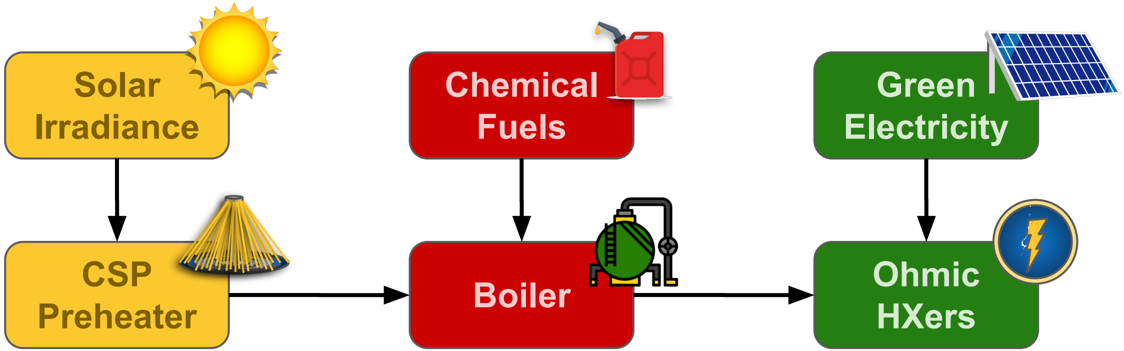

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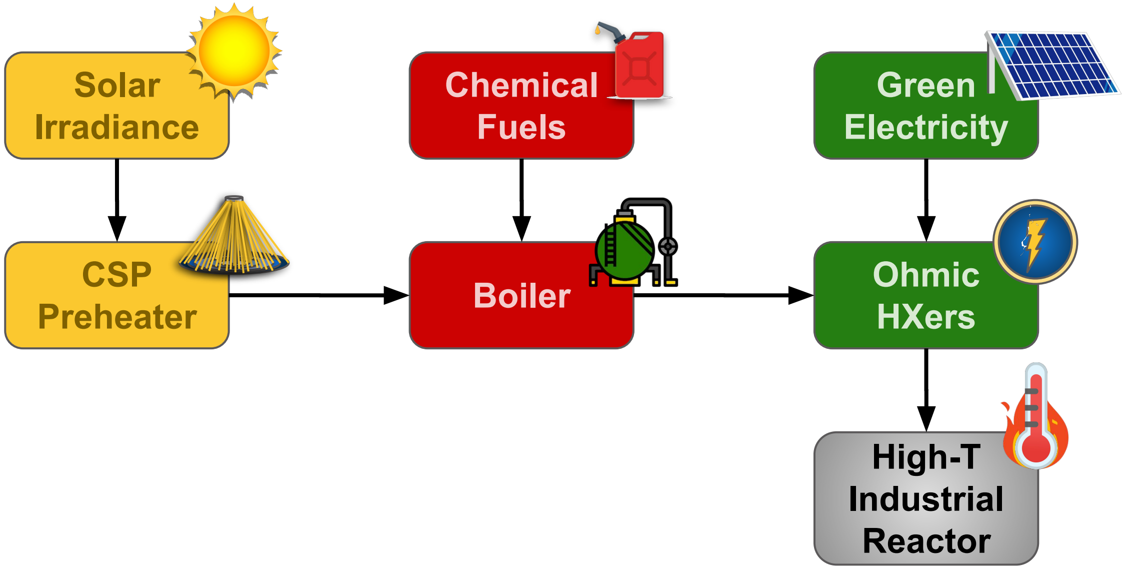

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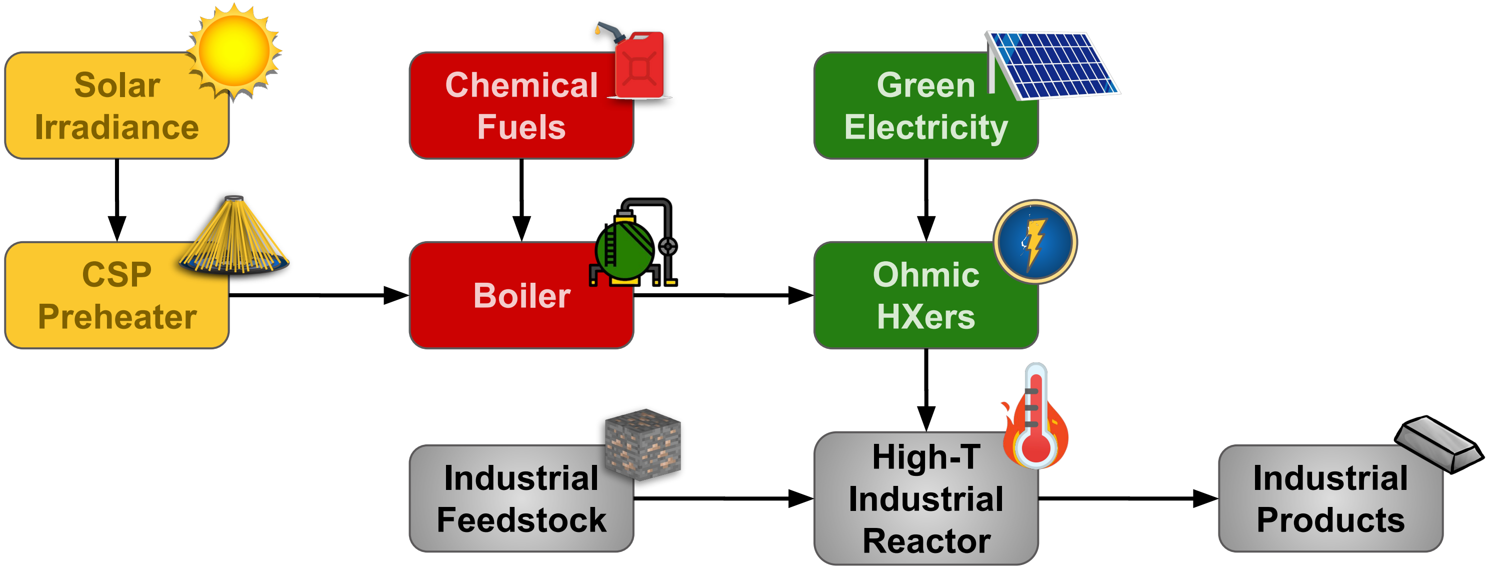

Ohmic (Joule) Heat Exchangers

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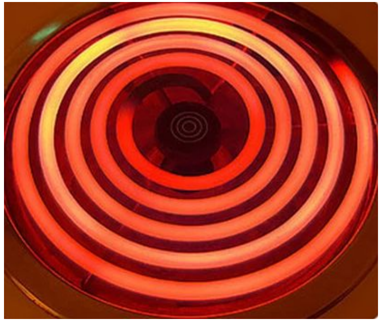

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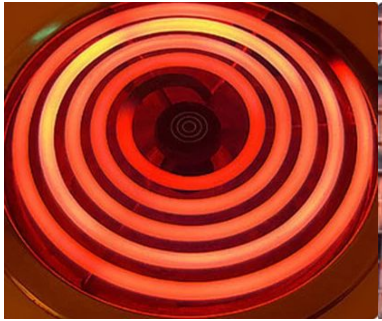

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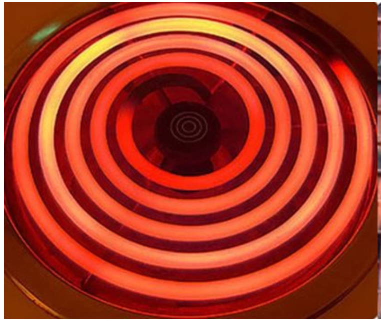

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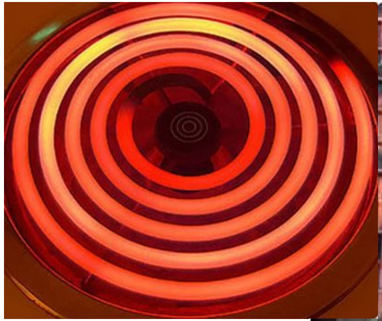


Ohmic (Joule) Heat Exchangers

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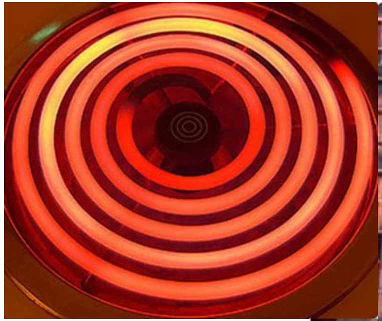


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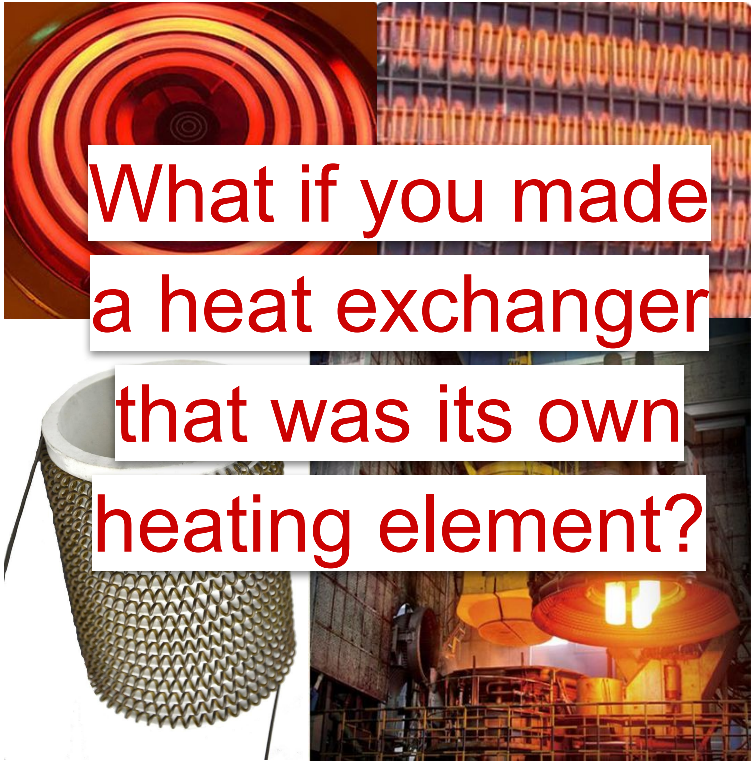

Electroceramic Heating Elements

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Ceramic Conductors. In *Electroceramics*; **2003**; pp 135–242.

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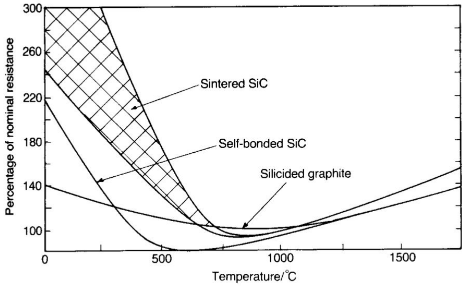

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J. Alloys Compd. **2019**, *780*, 156.

Ohmic Heating: Control Systems

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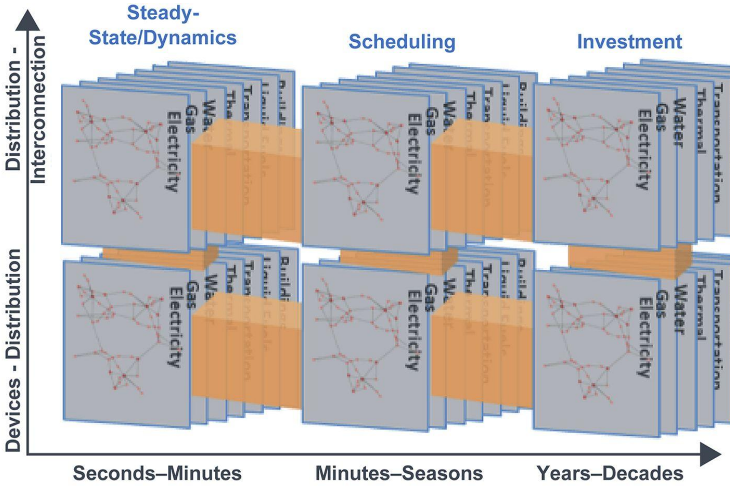
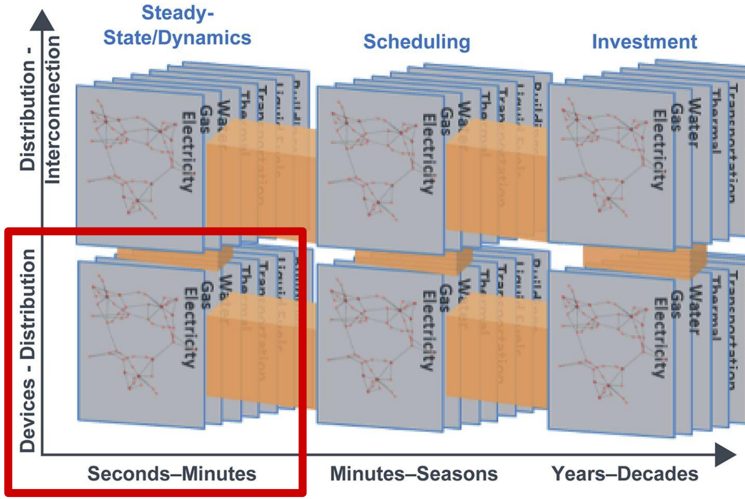


Joule **2021**, *5*, 47.

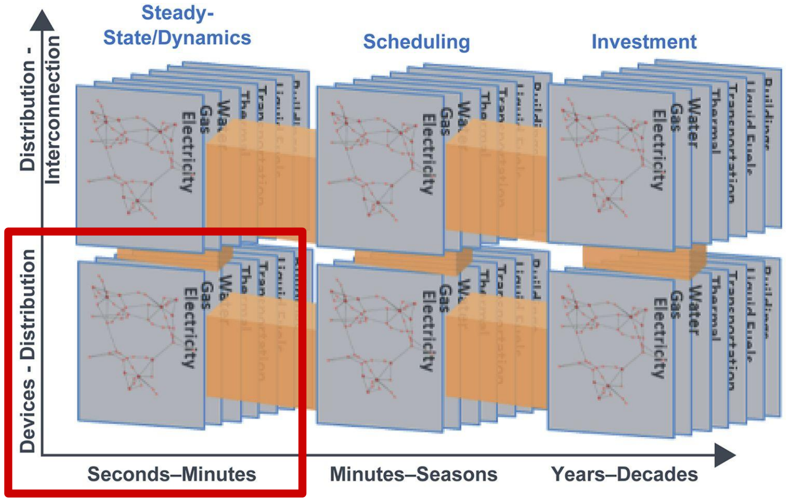
Ohmic Heating: Control Systems

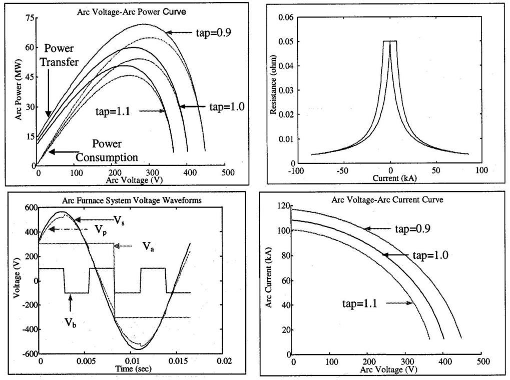


Joule **2021**, *5*, 47.

Ohmic Heating: Control Systems

Rapid, quantitative feedback



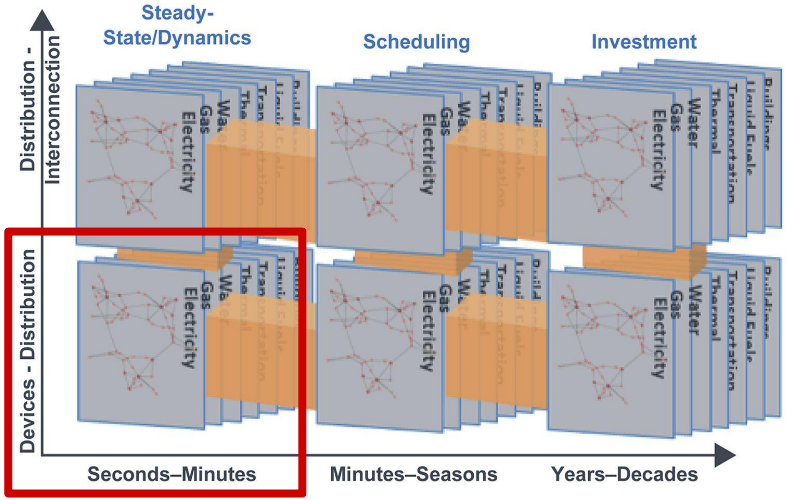


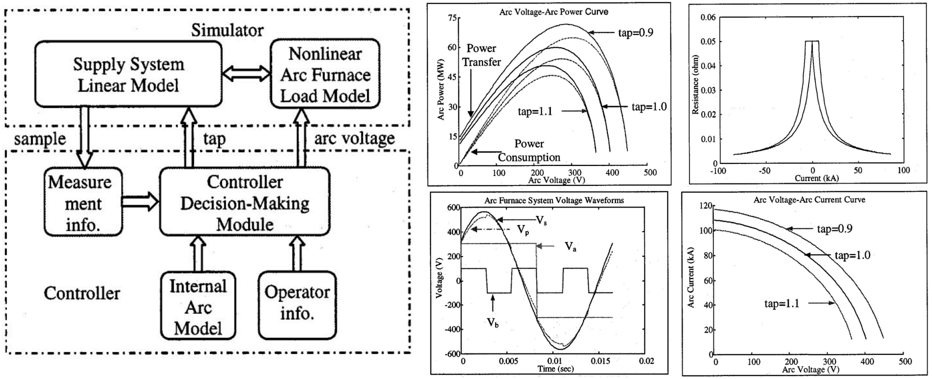
Joule **2021**, *5*, 47.
IEEE Trans. Power Deliv. **2000**, *15*, 931.

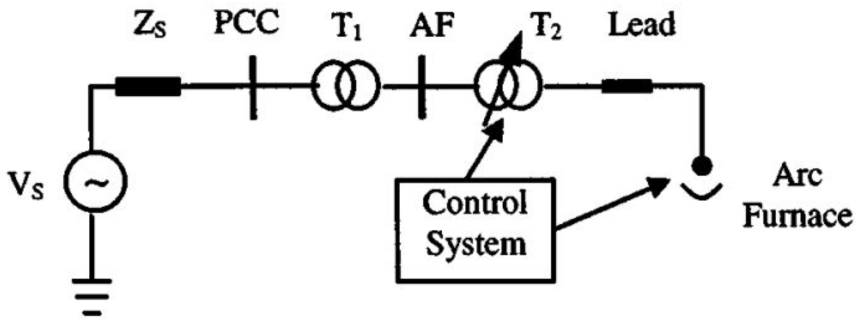
Ohmic Heating: Control Systems

Rapid, quantitative feedback

→ ripe for neural networks







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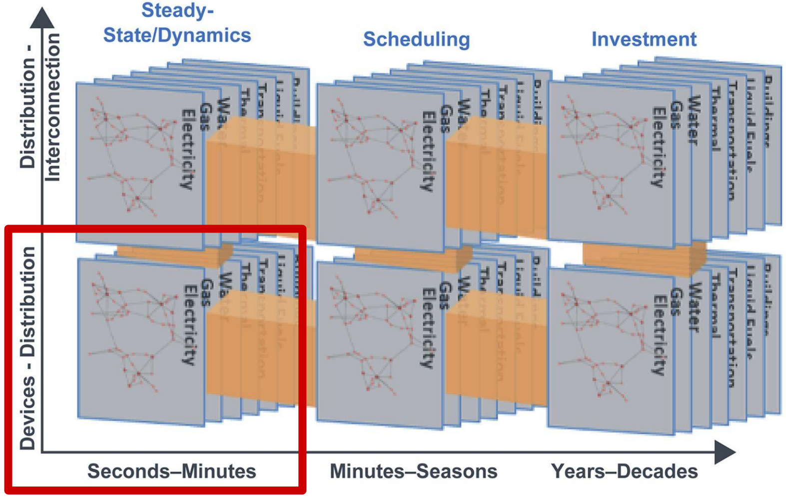

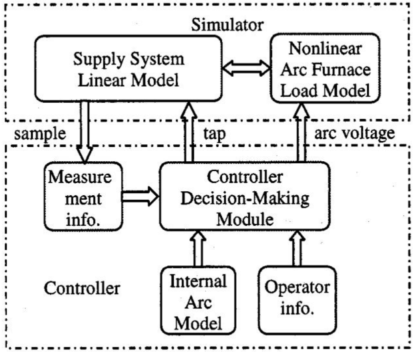

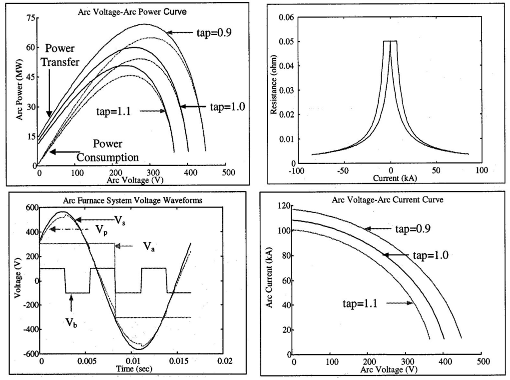

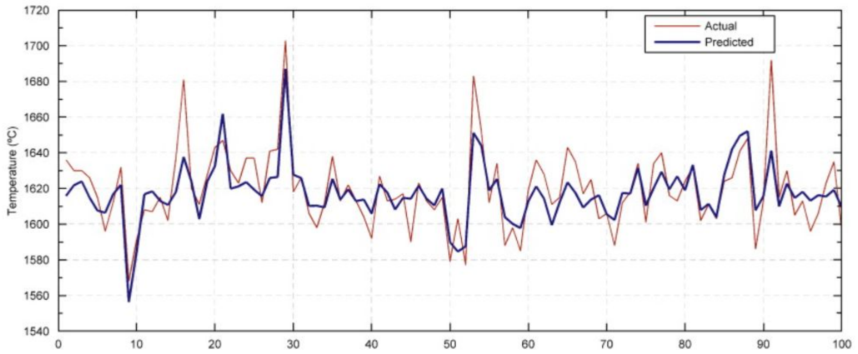

Joule **2021**, *5*, 47.
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Eng. Appl. Artif. Intell. **2008**, *21*, 1001.

Additive Manufacturing Electroceramics

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- Enables novel (difficult-to-machine) HX configurations

J. Alloy Compd. **2017**, *696*, 67.

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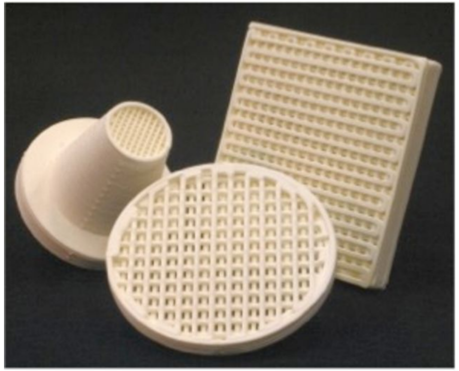

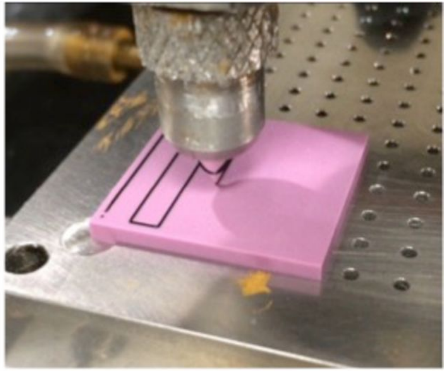

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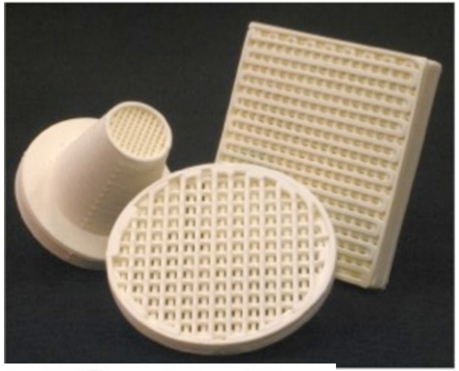

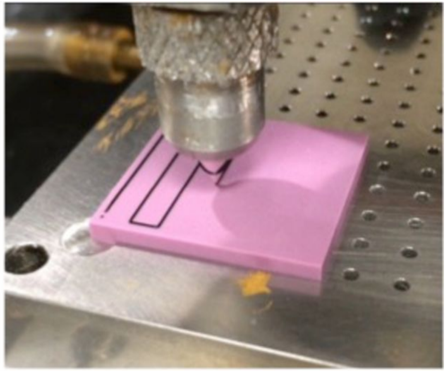

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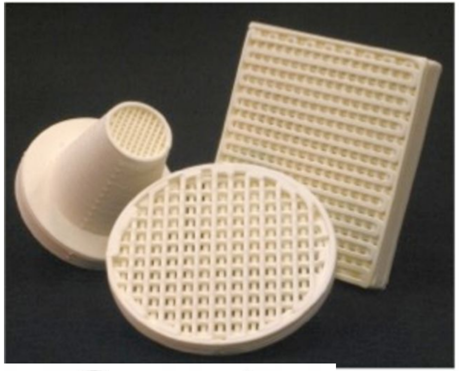

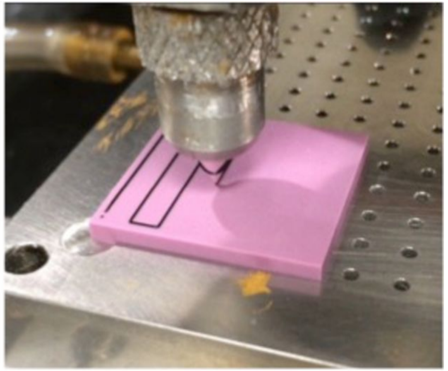

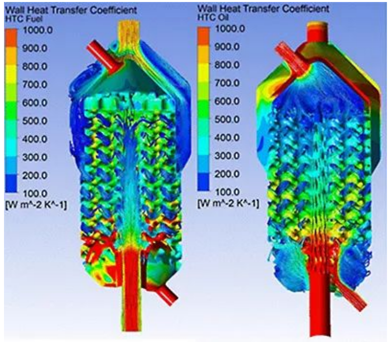

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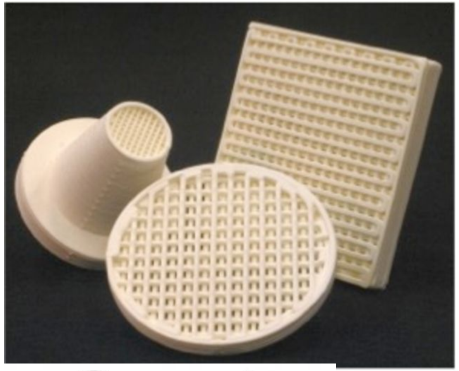
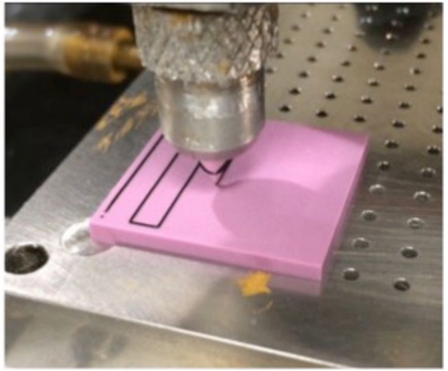
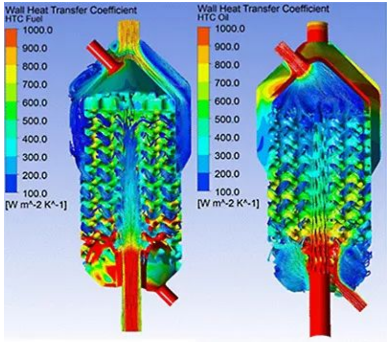
- SiC, $MoSi_2$, $LiSiO_3$ are demonstrated







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Xiangxia, W. *Fabrication of Electroceramics using Additive Manufacturing*. Ph.D. Thesis, **2018**.
Additive Manufacturing of Functional Ceramics. In *3D Printing for Energy Applications* **2021**; pp 33–67.
Zaengle, J. T. H. C. *Additive Manufacturing of YSZ and Lithium Silicate Electroceramics for Energy Generation and Storage*. Ph.D. Thesis, **2021**.

Outlook & Recommendation

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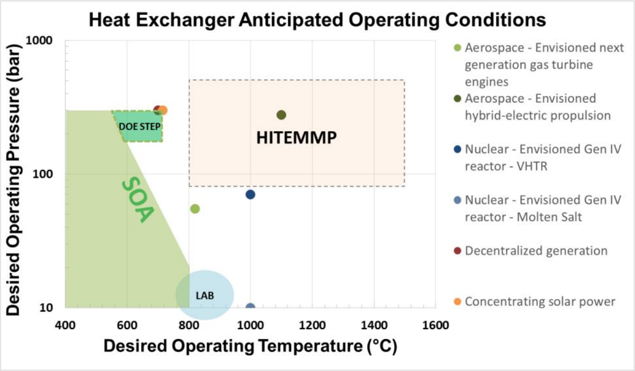
- High compatibility with HITEMMP



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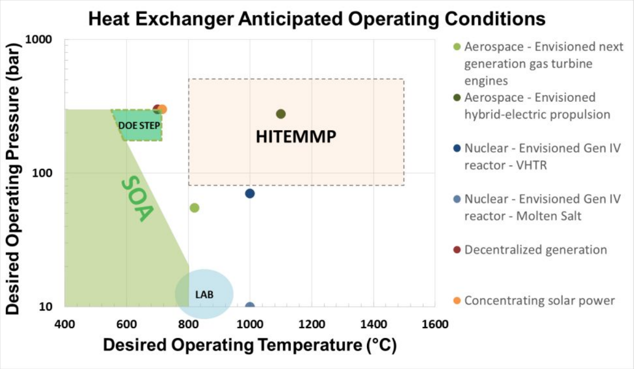

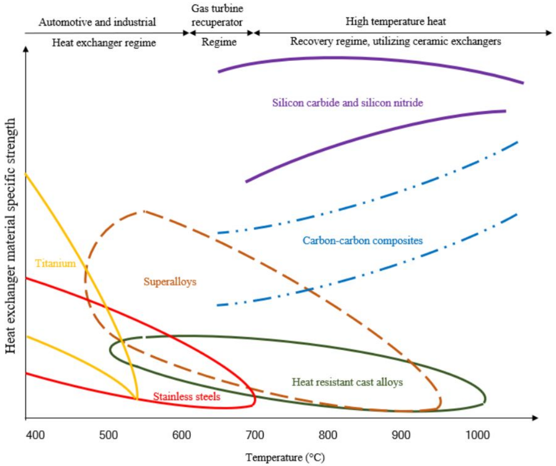

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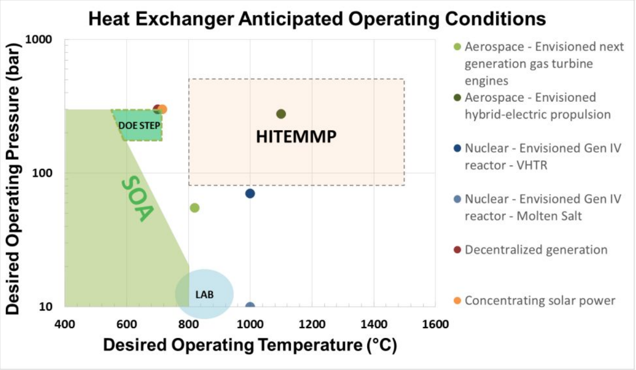
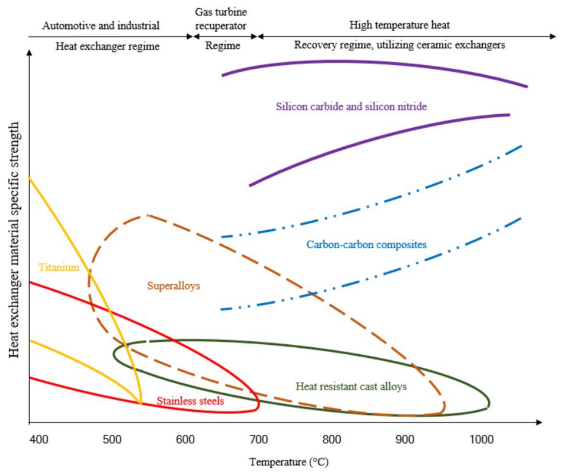
  - AM of TPMS HXers overlaps with *Topic S: Topology Optimization* Exploratory Topic





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- Simulate/develop ternary/quaternary hybrid energy systems

Example Projects

- Novel methodologies/substrates for electroceramic additive manufacturing
  - Cost reductions for raw materials / infiltration
- HXer designs with integrated ohmic heating
  - Modeling of 3D ohmic heat spreading
- Simulate/develop ternary/quaternary hybrid energy systems **(unprecedented?)**

Proposed Categories & Metrics

Proposed Categories & Metrics

Multi-Input Hybrid Energy Systems

Proposed Categories & Metrics

<u>Multi-Input Hybrid Energy Systems</u>

- Process heat quality:

Proposed Categories & Metrics

Multi-Input Hybrid Energy Systems

- Process heat quality:
  - Deliverable T (→ 1500 °C)

Proposed Categories & Metrics

<u>Multi-Input Hybrid Energy Systems</u>

- Process heat quality:
  - Deliverable T (→ 1500 °C)
- System performance:

Proposed Categories & Metrics

<u>Multi-Input Hybrid Energy Systems</u>

- Process heat quality:
  - Deliverable T (→ 1500 °C)
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$$\mathrm{LCoE_{CHP}} = \frac{\mathrm{CAPEX} \times \mathrm{CRF} + \mathrm{OPEX}}{E} - \frac{H}{E} * H_{\mathrm{price}}$$

$$\mathrm{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1}$$

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Ohmic Heat Exchangers

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Ohmic Heat Exchangers

- Material Design:

Proposed Categories & Metrics

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- Material Design:
  - T stability (MP, thermal shock / chemical oxidation resistance)

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  - Resistivity (Ω·m; case-by-case)
  - Cost ($/kg)

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  - Cost ($/kg)
- Heat Exchanger Design:

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  - Cost ($/kg)
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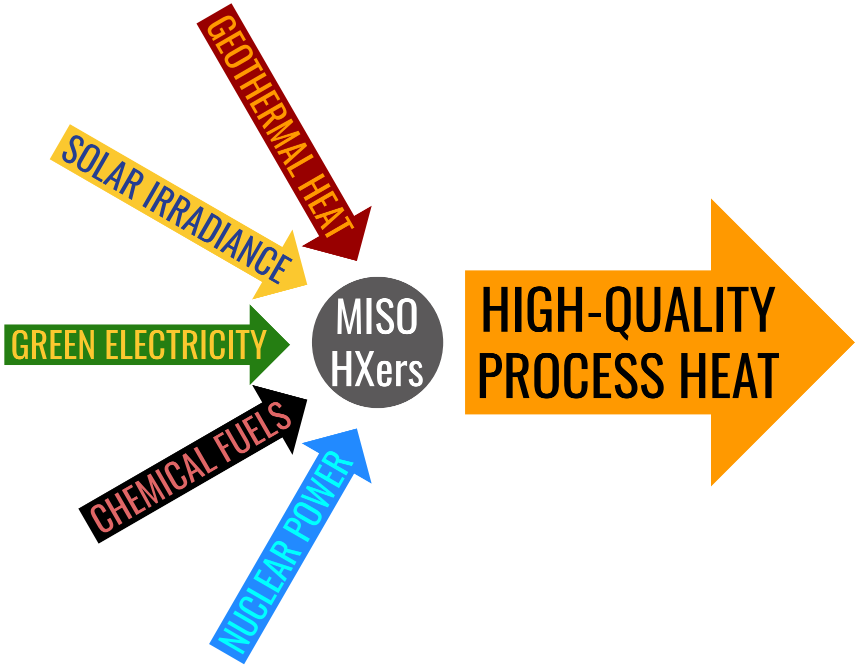
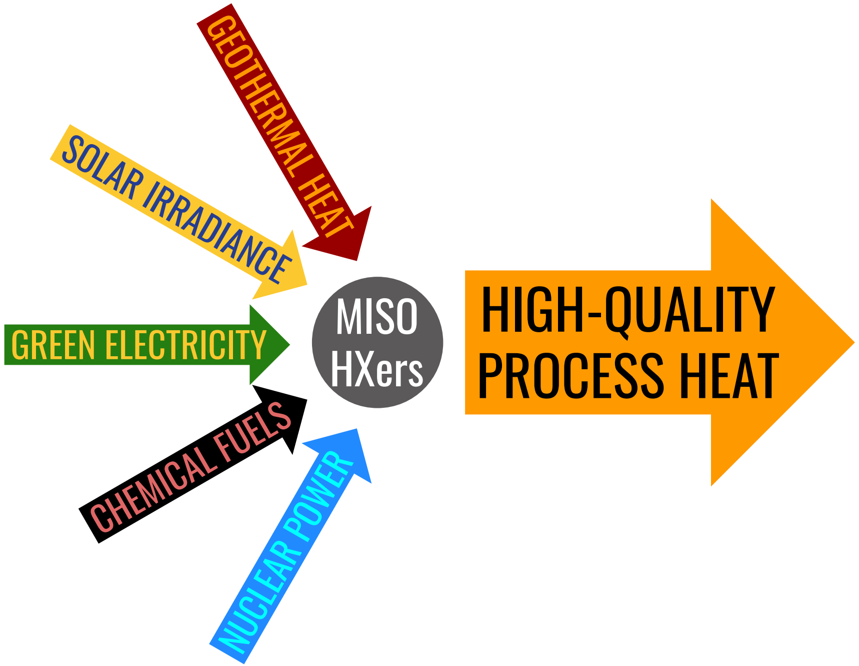
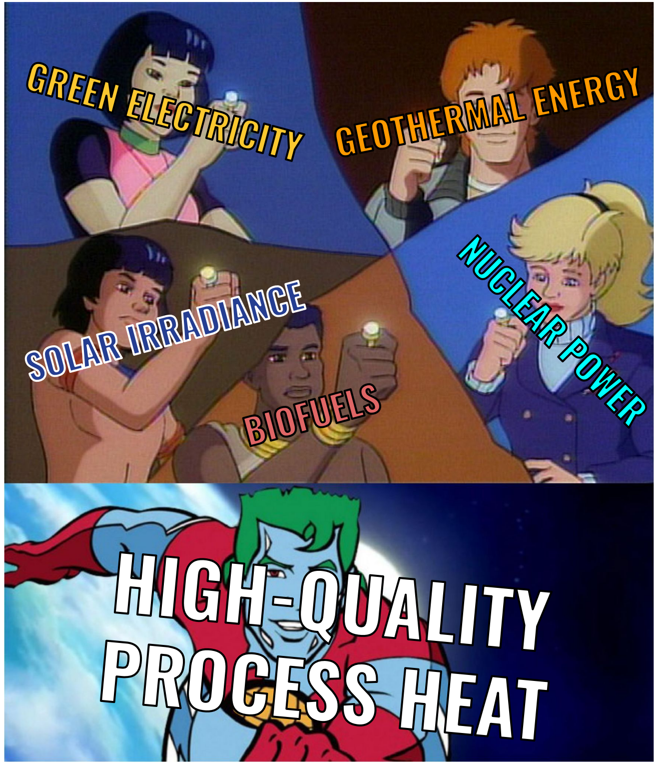
  - Specific power density (kW_{th}/kg)
  - Volumetric power density (kW_{th}/m^3)
  - Mean time-to-failure (kilo-hrs)
  - Manufacturability ($·°C/$kW_{th}$)

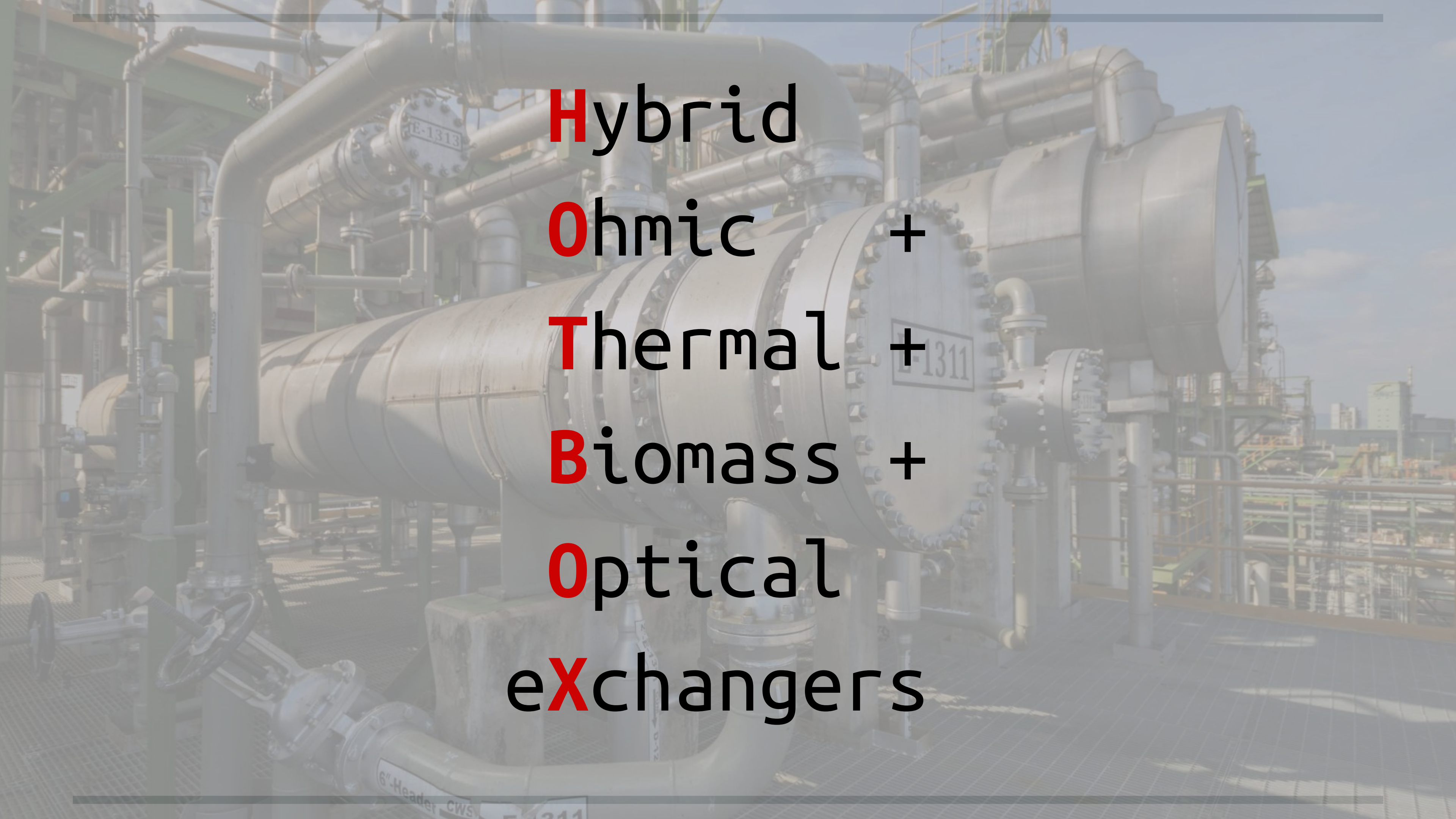
By These Power [Systems] Combined…



By These Power [Systems] Combined…







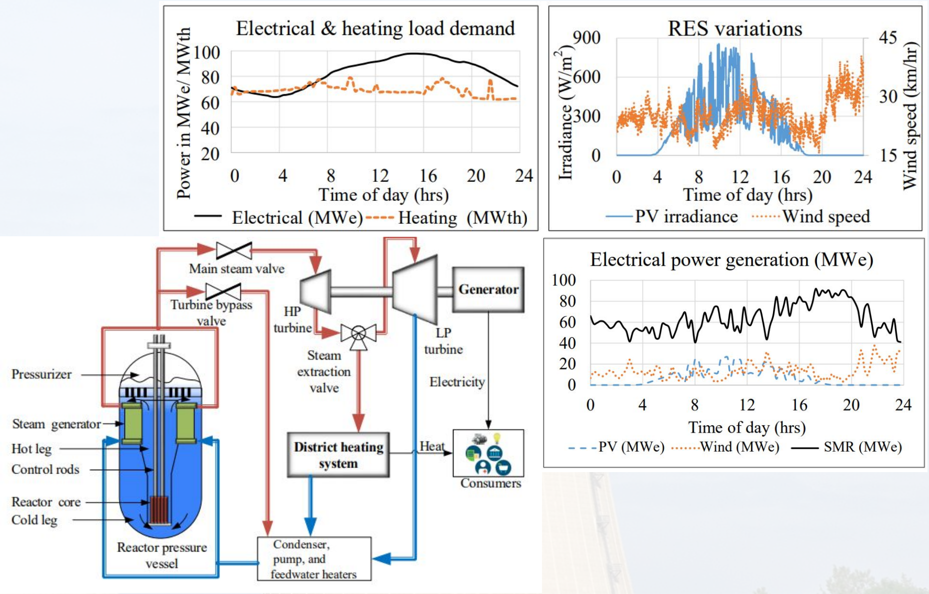
Hybrid
Ohmic +
Thermal +
Biomass +
Optical
e**X**changers

Bonus Slides

i sure hope i don’t end up having to use any of these

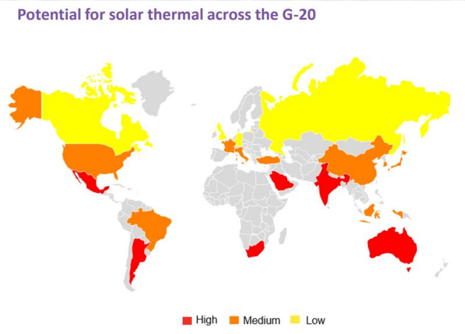
Nuclear Heating

- Small Modular Reactor (SMR) hybridization with PV has been studied



IEEE Trans. Energy Convers. **2021**, *36*, 2794.

Challenges for CSP



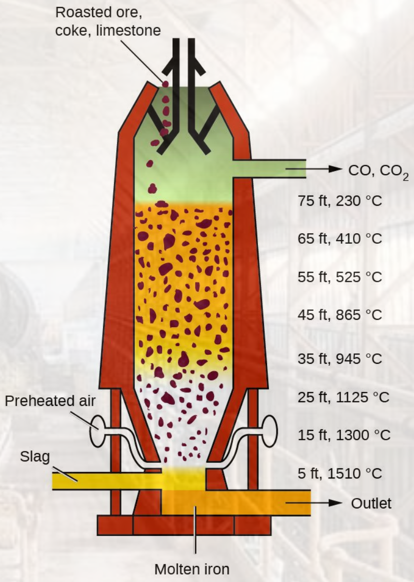
- Localized, intermittent
- Difficulty of TES
  - 2nd-gen nitrates: decompose at ~560 C
  - Chloride salts: good to 800 but corrosive w/ H_2O
  - Solid-particle: good to >800 but parasitic energy cost of fluidization, particle loss, accelerated abrasion
  - Latent/TCES is so goddamn messy
- T limitation: parabolics hard to break 550, can get to 700 C w/ next-gen insulation but emittance is just too high
  - Power towers can get to 800~1000?

Concentrated Solar Heating

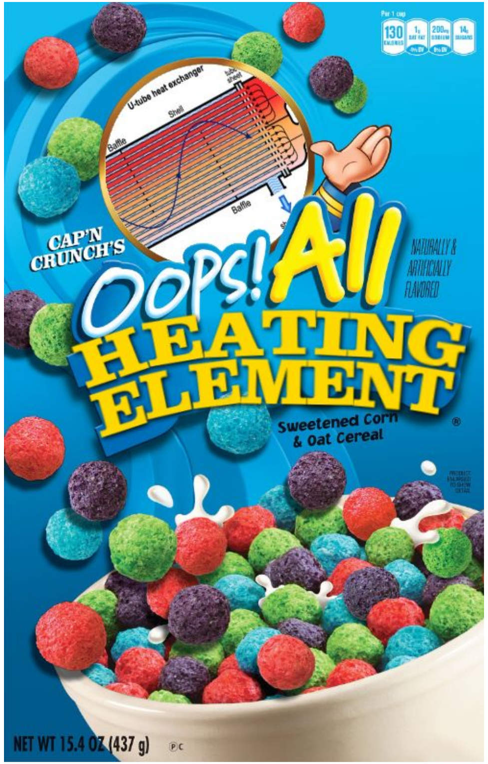
Consolidate CSP preheating (receiver-reactors)

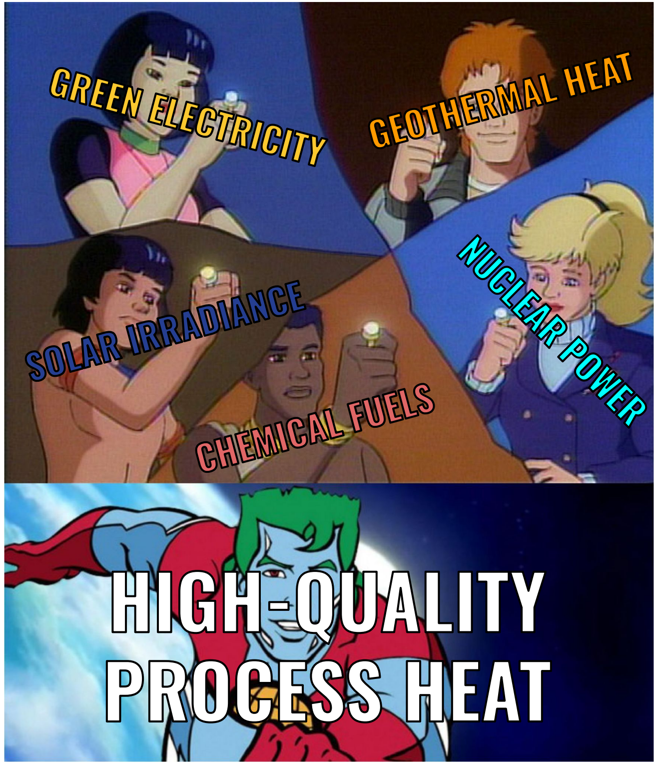
Challenge: good receivers by definition have good emissivity (high SA), are near ideal black-bodies

→ will radiate heat well, poor HXers


Roasted ore,
coke, limestone
CO, CO2
75 ft, 230 °C
65 ft, 410 °C
55 ft, 525 °C
45 ft, 865 °C
35 ft, 945 °C
25 ft, 1125 °C
Preheated air
15 ft, 1300 °C
Slag
5 ft, 1510 °C
Outlet
Molten iron

why did i make this





Traditional

- Historically, Ohmic heating is rarely used because electricity is among the most expensive forms of energy
  - This calculus would change if PV fell to 2¢/kWh
- Widespread Ohmic heating still has problems:
  - Intermittency (still needs to function cheaply at night)
  - Mechanism of Ohmic heat transfer is not great!
    - $MoSi_2$ elements (good to 1200 C) are expensive, fragile, and can burn out easily
- Solution: 3-D electroceramic elements -- no single point of failure!

Ohmic Heating

Electroceramics/thermoelectrics:

- HXers that are also Ohmic heating elements

Additive manufacturing:

- Allows for next-gen HX designs (gyroids)
- Compatibility with electroceramics?

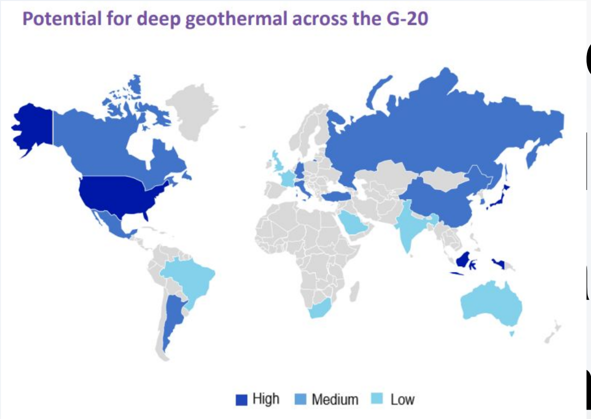
Heat element design: $MoSi_2$, others?

Challenge: cost, control systems

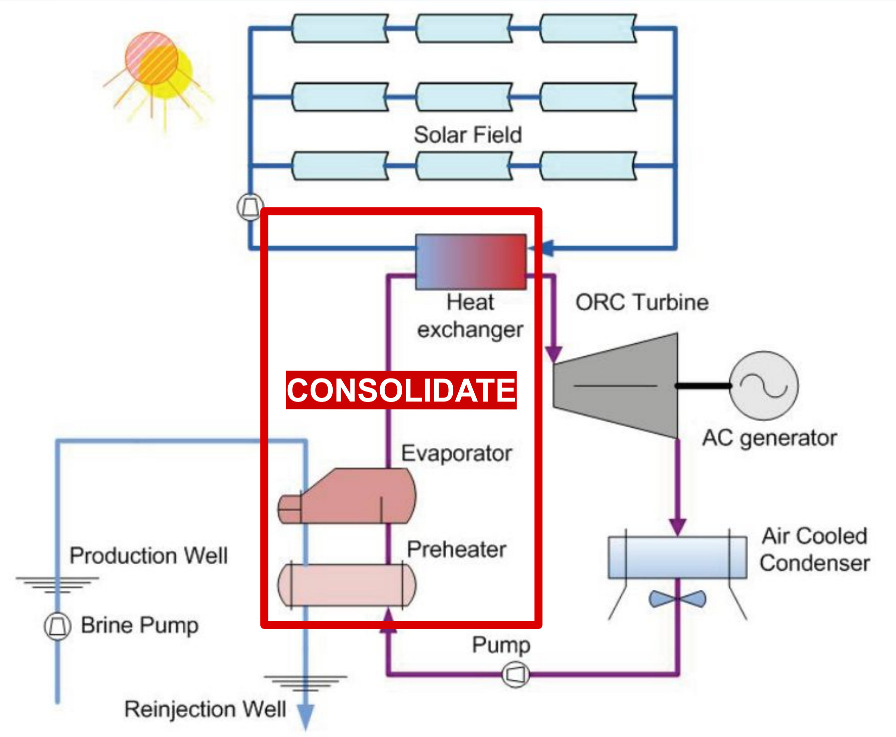
Overview

1. Motivation (industrial decarb)
2. Incumbent tech
    a. HXers, boilers, arc furnaces
    b. Flaws of CSP, geothermal, PV/wind
3. Inspiration (Hybrid CSP/geothermal)
    a. Hybrid Energy Systems (MISO)
4. CSP for boiler feedwater
5. Ohmic exchangers
    a. Challenges of industrial Ohmic heating
    b. Additive manufacture of electroceramics
    c. Triply periodic minimal surface HXers
    d. Ohmic control systems (analogy to arc furnaces)
6. Outlook
    a. Compatibility with HITEMMP and Topologies
7. Example projects and metrics
8. HOTBOX

Inspiration: hybrid geothermal/CSP



- eotherma
- lized,
- r, etc.
- l T slowly drops over time
    - → supplement w/ CSF

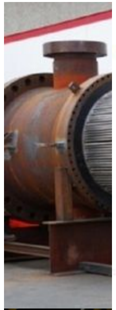


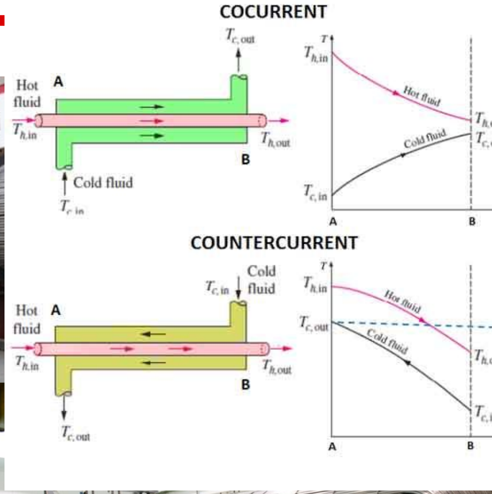
INL/CON-14-32101; Idaho National Lab. (INL), Idaho Falls, ID (United States), **2014**.

Exergetics Define System Viability

- Series of HXers required
  - Feedwater heater, flue gas heater, superheater,
  - Series of fluids of increasing T
- Very very big!
  - Compact HXers have low market penetration
  - Difficult to compact b/c mass flow, residence time
- Q = U*A*LMTD $Q = U \times A \times LMTD$
  - Need to minimize TD for direct heat transfer
    → series of HXers needed for exergetic efficiency

$$LMTD = \frac{\Delta T_A - \Delta T_B}{\ln\left(\frac{\Delta T_A}{\Delta T_B}\right)} = \frac{\Delta T_A - \Delta T_B}{\ln \Delta T_A - \ln \Delta T_B}$$





Boilers / Combustive Heating

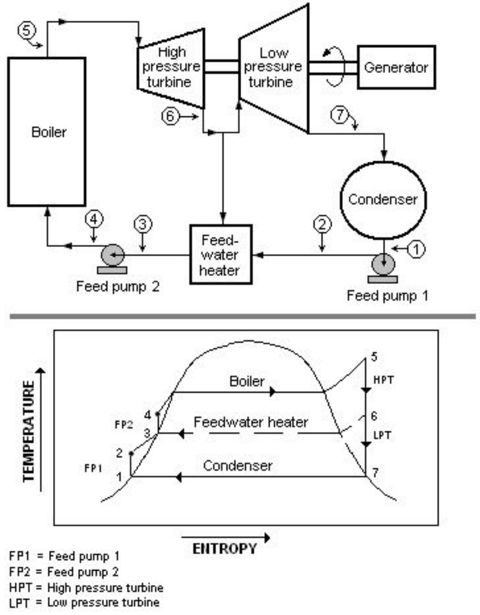
Replace feedwater heaters w/ e.g. CSP

Temp ranges:

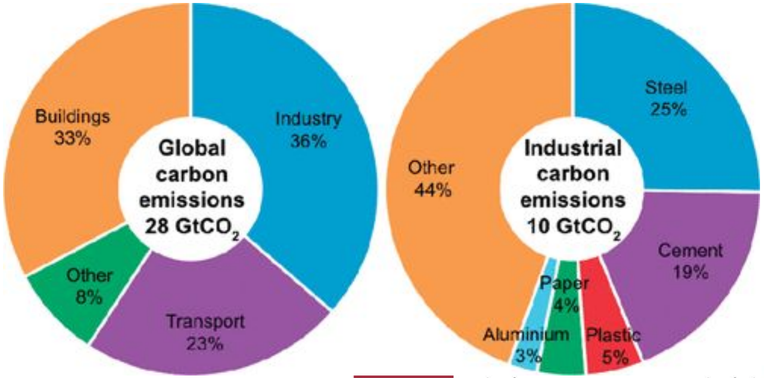
Hydrocarbons (methane, LPG, k

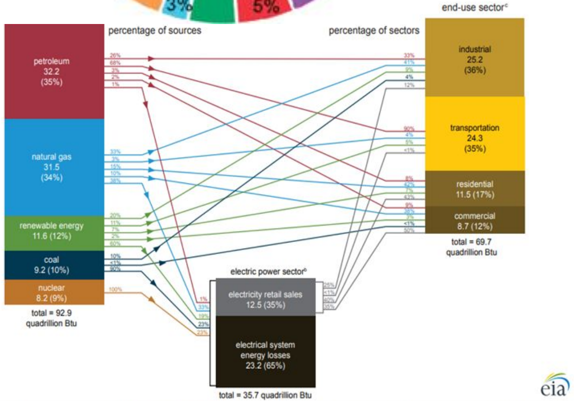
diesel, oil…biofuels?): all ~2000 C

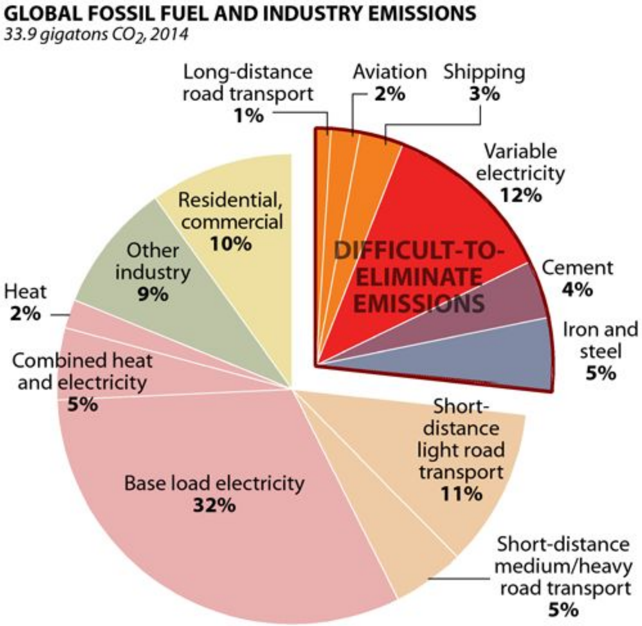
Hydrogen: ~2000 C (air); 2660 C



Deshmukh, Y. V. *Industrial Heat*





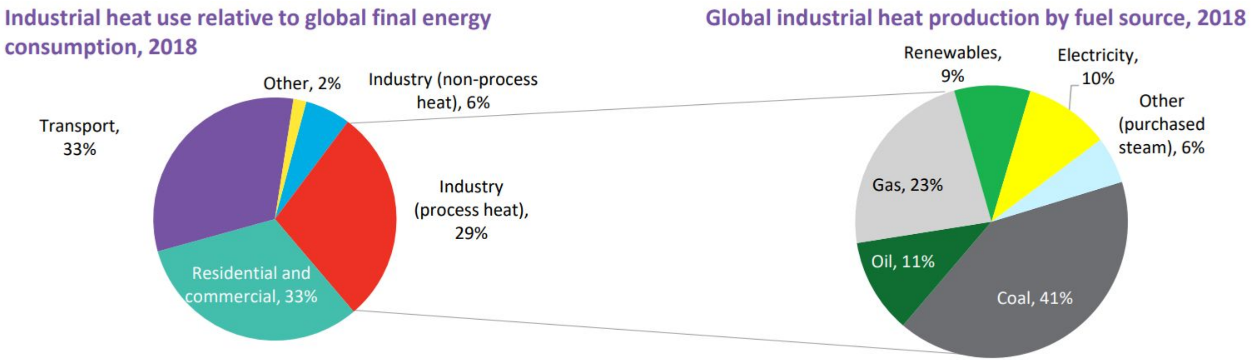


US EIA *Monthly Energy Review*, **2021**.
Science **2018**, *360* (6396), eaas9793.
Environ. Sci. Technol. **2010**, *44*, 1888.

Motivation

~2/3rds of industrial energy consumption is for process heat (~30 quads)

10~20% of anthropogenic emissions



Solar Thermal Process Heat (SPH) Generation. In *Renewable Heating and Cooling*; **2016**; pp 41–66.
Decarbonizing Industrial Low- to Medium-Temperature Heat. *BloombergNEF*, **2021**.

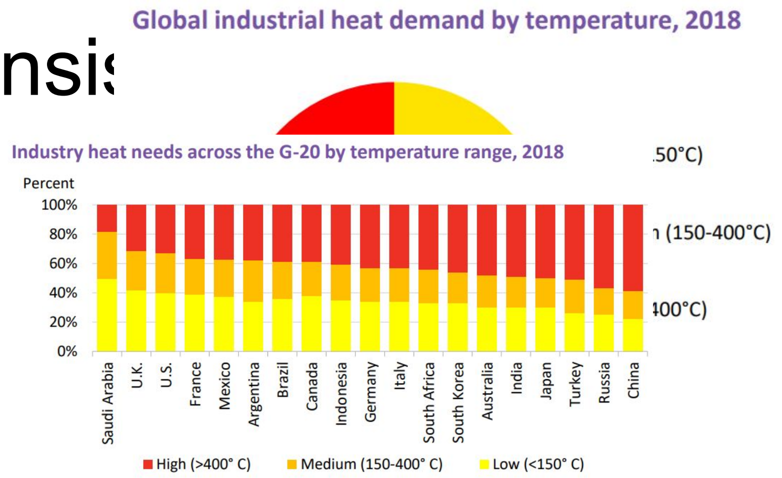
Challenge/Inherency

Process heat requires consis

heat

e.g. iron+concrete (sin

industrial emissions) requ



Intermittent renewables provide low-quality heat (e.g. CSP Ts barely up to 700 C) incumbent sustainable energy sources can't decarbonize high-T industrial reactions (~10% of anthropogenic emissions) without revolutionary breakthroughs. but with hybrid heat exchangers you synchronize multiple sustainable energy inputs to achieve the same effect but without having to hit moonshot targets for any of the constituent energy systems

Types of energy input:

- CSP
- Combustion
- Ohmic (electricity) -- PV, wind
- Geothermal
- Nuclear

Advantages and disadvantages:

- CSP: T limited (<550~850 C)
- Combustion: needs CCS for near net-0
- PV, wind: intermittent
- Geothermal: localized
- Nuclear: CAPEX, waste

New technologies

Modular/Hybrid heat exchangers that take multiple energy inputs simultaneously

E.g. geothermal/CSP for sustainable "baseload" heat

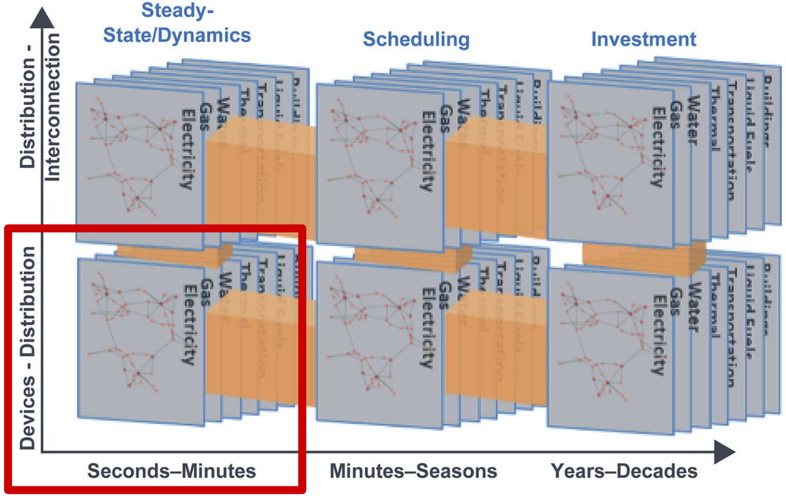
combustion/Ohmic heating for "last-mile" heating

Control Systems Targets

Material requirements

Control requirements

Technoeconomics?



Joule **2021**, *5* (1), 47.

Ohmic Heating: Elements

- Typical resistivity: 0.01–1 Ω·m
  - Need to match impedance with available power
  - Good match for rods ~1m long, ~1cm diameter
  - Can be modulated by doping (e.g. SrO in $LaCrO_3$)
  - Resistors are typically 10^3~10^8 Ω, conductors are typically <10^{-6} Ω·m
  - 11 cm 10^5 Ω resistor from 10^{-6} Ω·m material would require 10^{-12} m^2 cross-sectional area (i.e. 1 μm x 1 μm) → material design needs to fit physical use case
  - This is doable because electrical ρ spans ~15 orders of magnitude (thermal κ spans ~5)
- Refractories:
  - resistant to decomposition by heat, pressure, or chemical attack, retains strength and form at high temperatures
  - 70% of all refractories used in iron/steel
- Service life depends on atmosphere, glaze

J. South Afr. Inst. Min. Metall. **2008**, *106*, 1.
Ceramic Conductors. In *Electroceramics*; **2003**; pp 135–242.
J. Alloys Compd. **2019**, *780*, 156.

Incumbent Techologies

- This is kinda already done at small scale
  - H_2 SOEC goes in at 800 C, comes out at 750 C
  - Recycle 750 C output stream
  - Uses Ohmic heating for last 50 C of heating
    - Requires 3 separate HXers!!

HX metrics

Heat exchanger specific/volumetric power density (kW_{th}/kg & kW_{th}/m^3)

Mean time-to-failure (MTTF)

Manufacturability ($\$\cdot K/kW_{th}$)

Metrics/Technoeconomics

- Process heat:
  - Highest accessible T
  - ¢/kWh_{th} (as a function of process T)
- Hybrid capacity factor:
  - Avg. % of time system is operating at or above full rated output of its most energetic system
- Just plain # of energy inputs

J. Mater. Civ. Eng. **2021**, 33, 04021250.

Material Targets

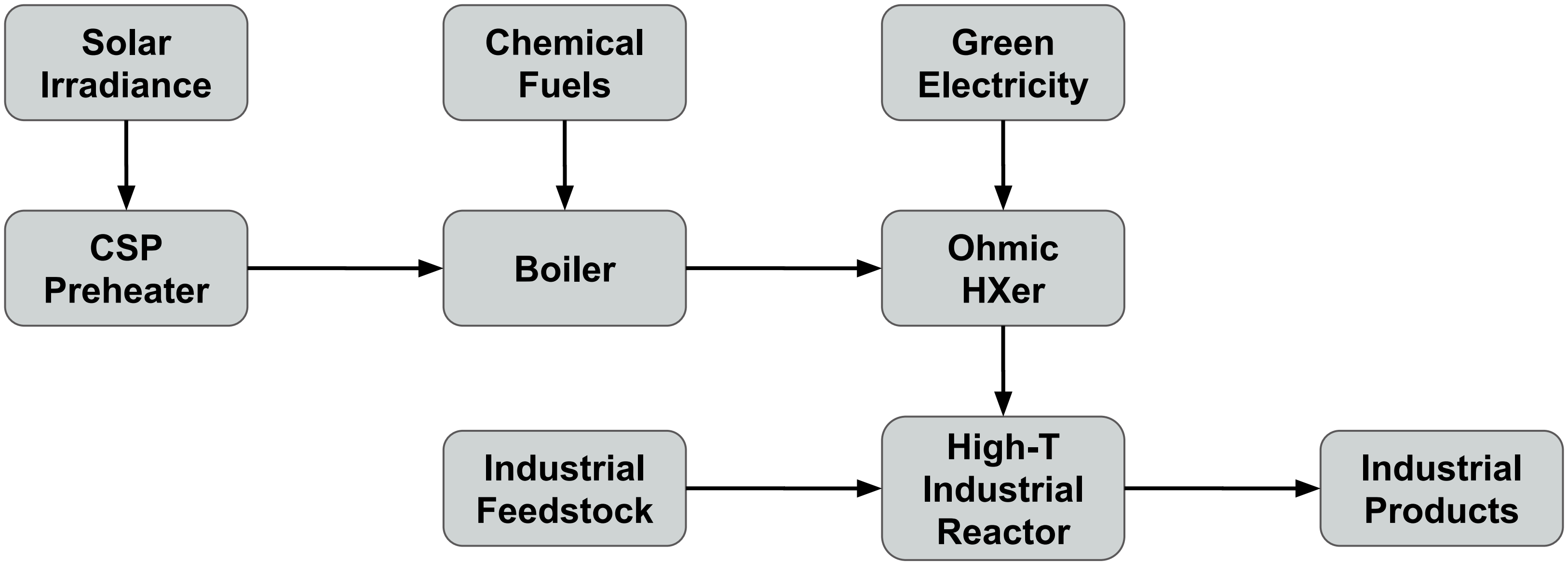
- T stability (MP, thermal shock, oxidation)
- Mechanical strength (tough for ceramics)
- Thermoelectrics: ZT~10
- Cost of heating elements / electroceramics

J. Alloys Compd. **2019**, *780*, 156.
Renew. Sust. Energy Rev. **2018**, *95*, 1.

Metrics/Technoeconomics

- Cement: 4-5 GJ/ton
  - Responsible for 40% of total cost
  - 222 kg CO_2 / ton cement (due to energy)
  - 530 kg CO_2 / ton cement (decarbonation)

J. Mater. Civ. Eng. **2021**, 33, 04021250.


Solar Irradiance
Chemical Fuels
Green Electricity
CSP Preheater
Boiler
Ohmic HXer
Industrial Feedstock
High-T Industrial Reactor
Industrial Products

Extant ARPA-E projects

HITEMMP:
https://arpa-e.energy.gov/technologies/programs/hitemmp

Topologies:
https://arpa-e.energy.gov/technologies/exploratory-topics/topology-optimization