Solar-to-Fuels Conversion:

a roadmap to making EVERYTHING solar-powered

Jonathan “Jo” Melville
SETO Ideafest Pitch
March 8th, 2022

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy

Fossil Fuels are Bad [citation needed]

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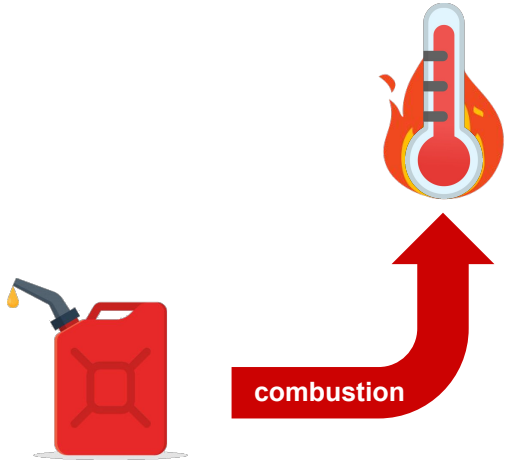

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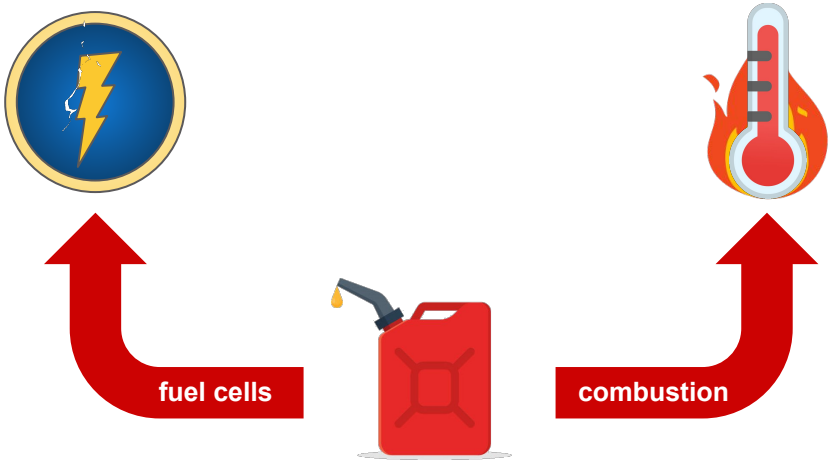

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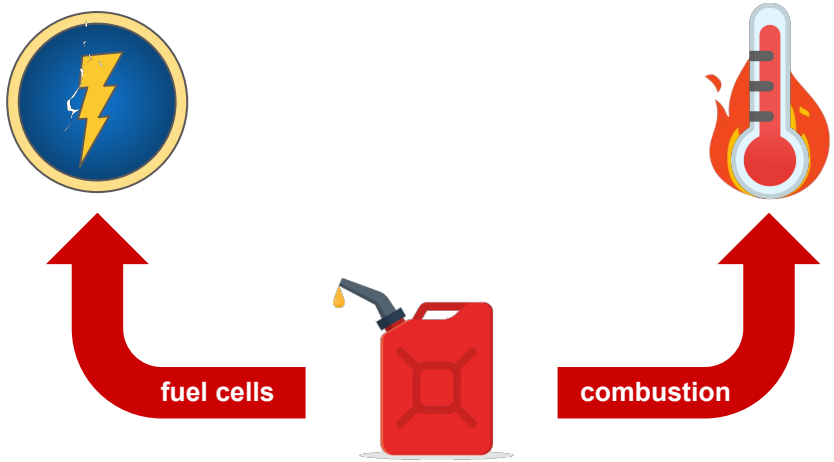

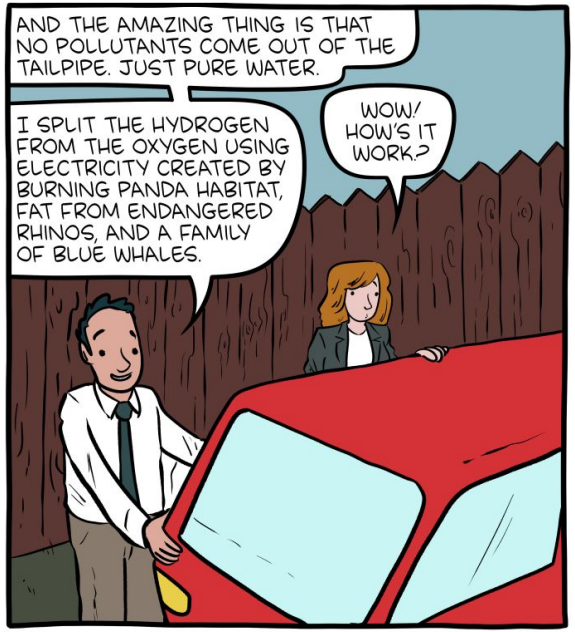

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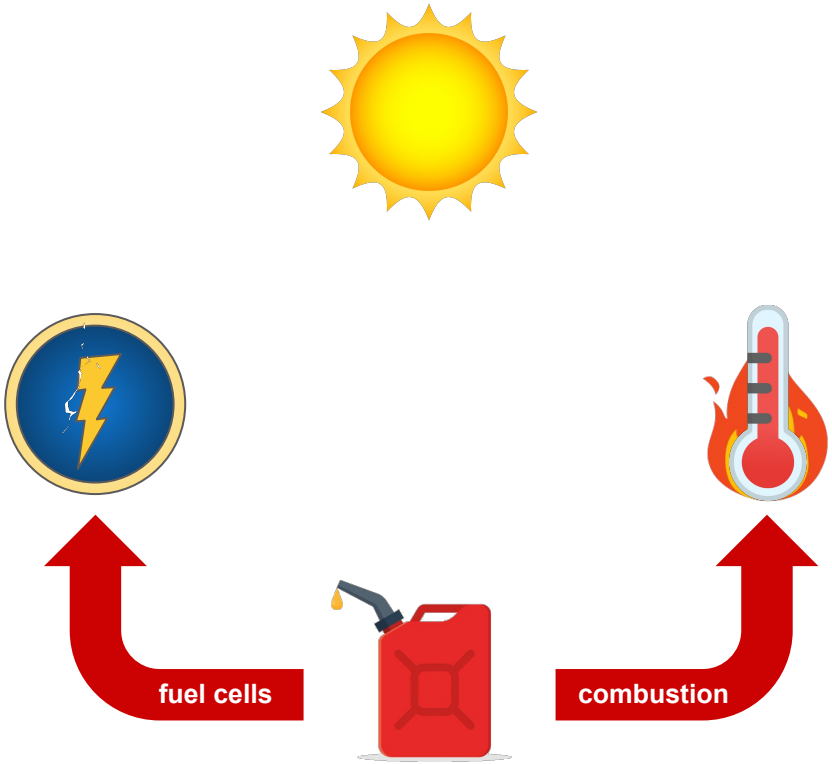
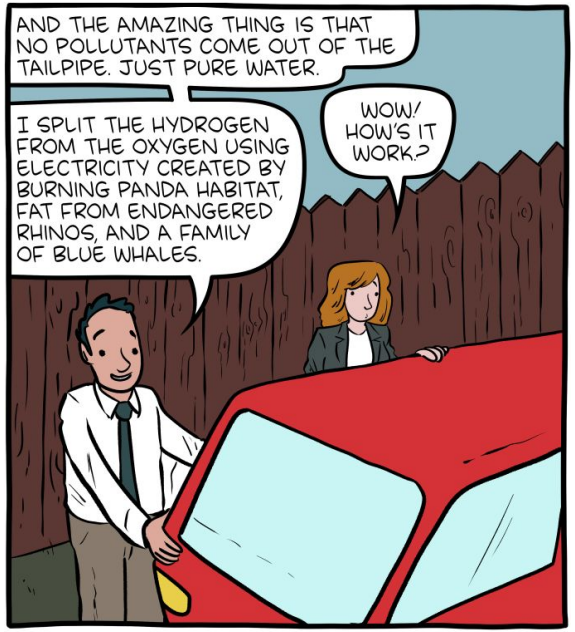
Weinersmith, Z. *Saturday Morning Breakfast Cereal*, February 19, 2022.

Solar Power is Great! [citation needed]





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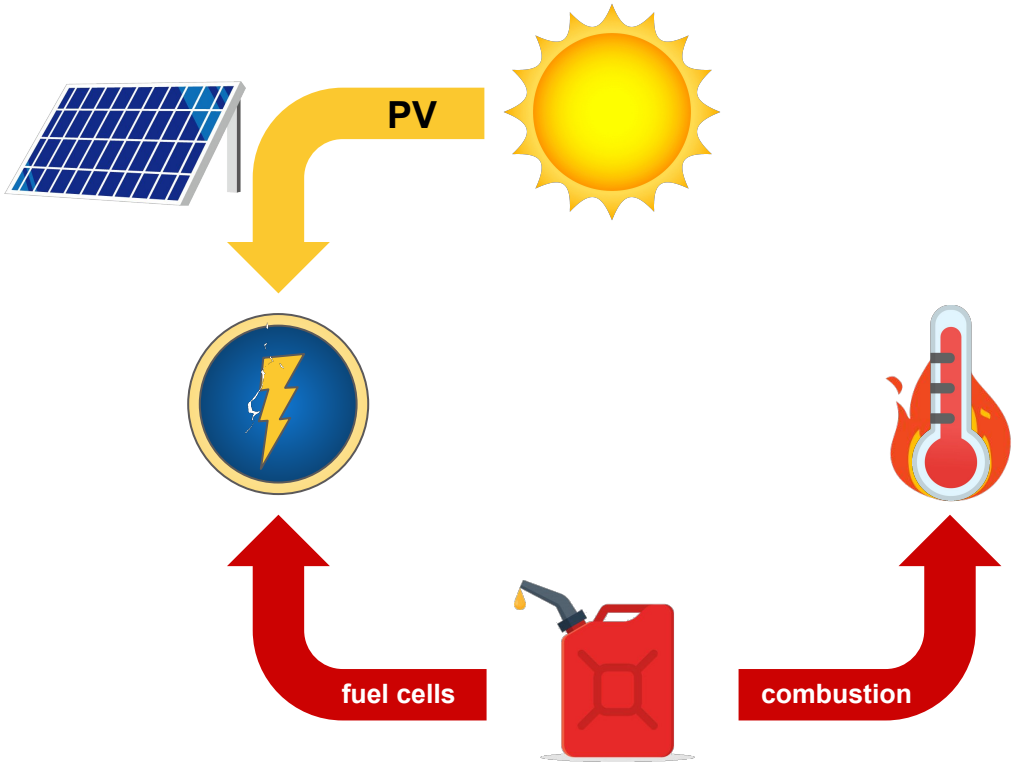

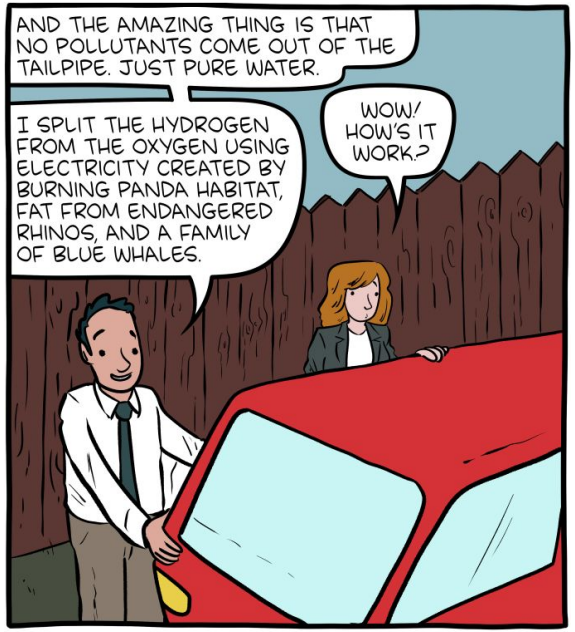

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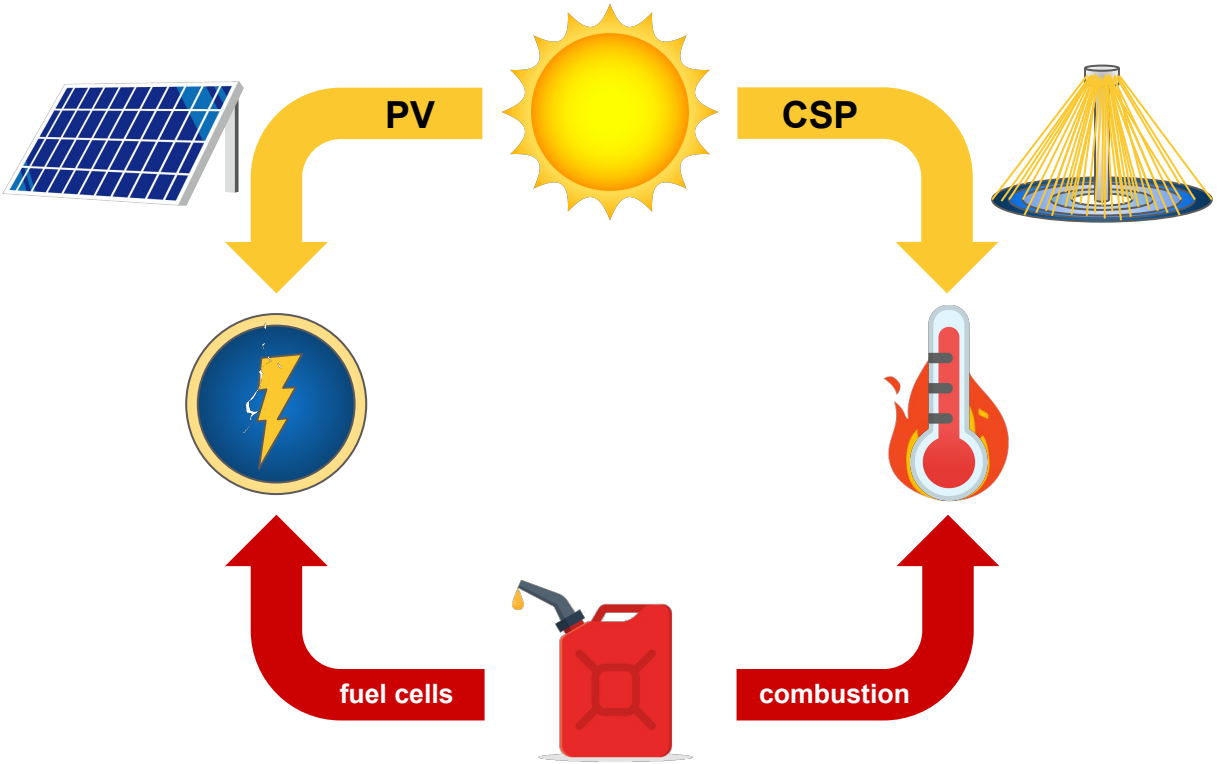

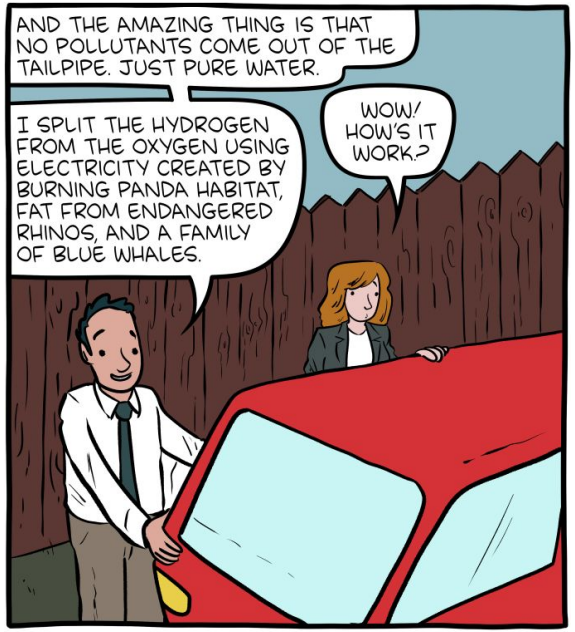

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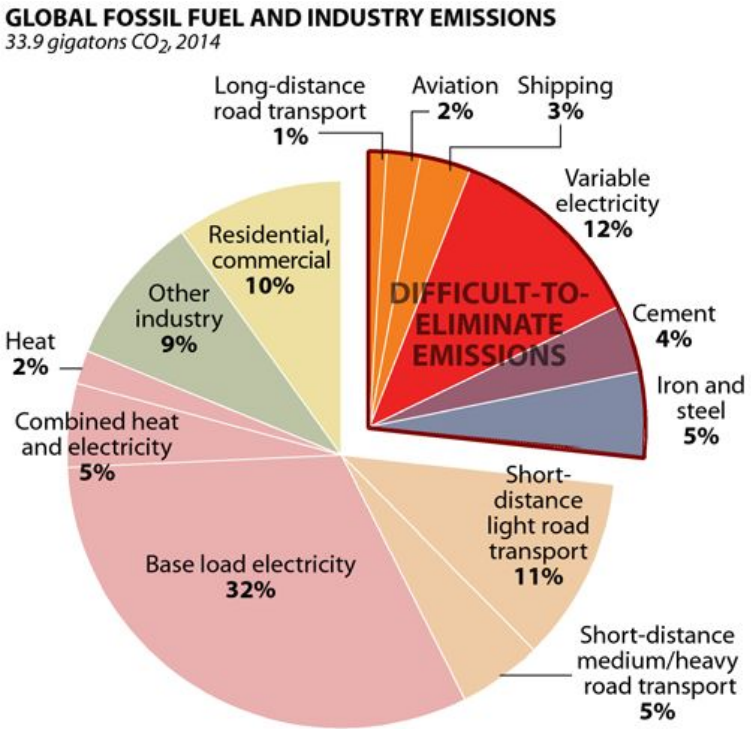
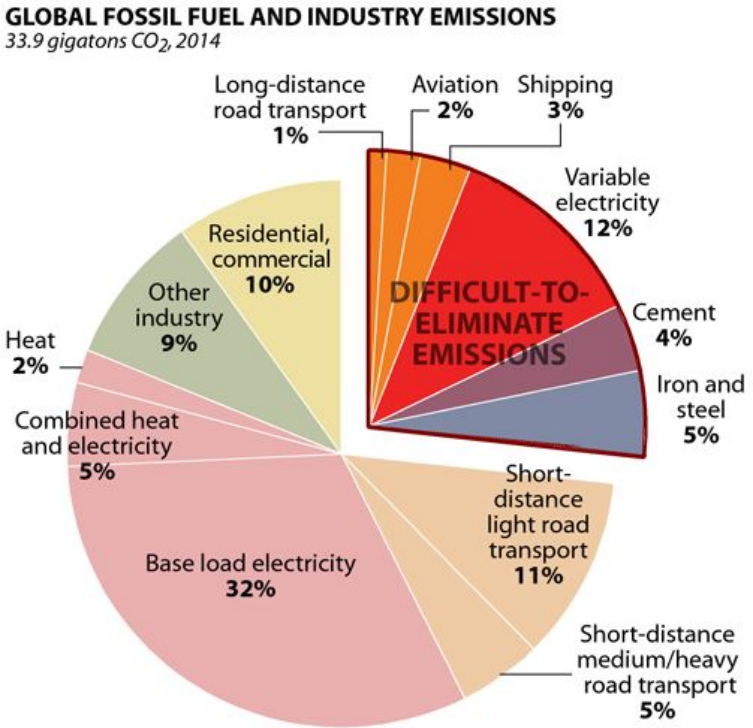


Science **2018**, *360* (6396), eaas9793.

…but it can't do everything (yet)

- ~30% of emissions are *"difficult to decarbonize"*



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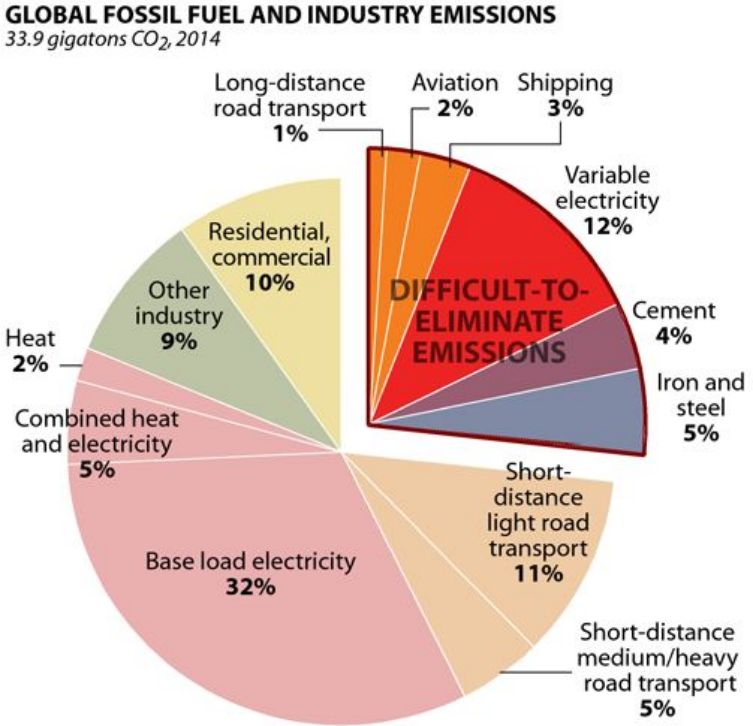

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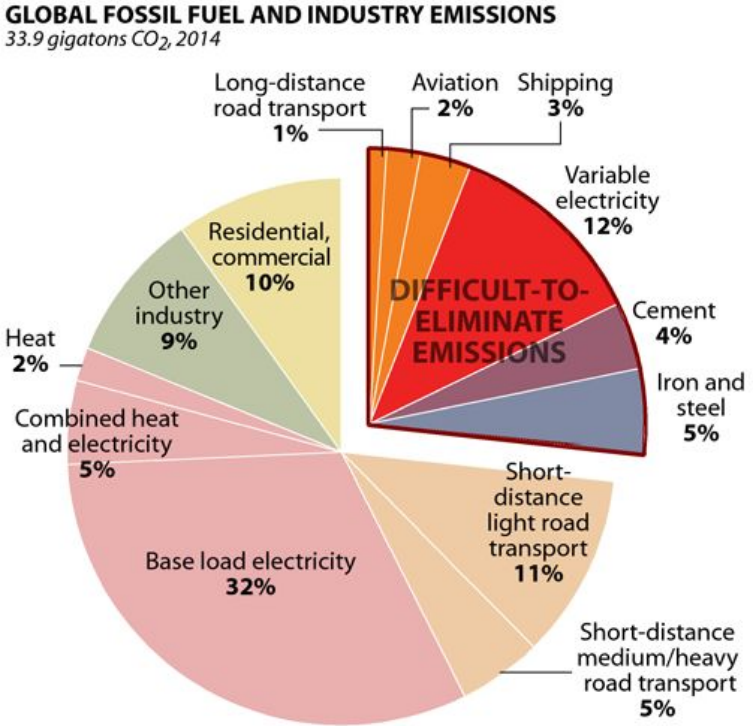

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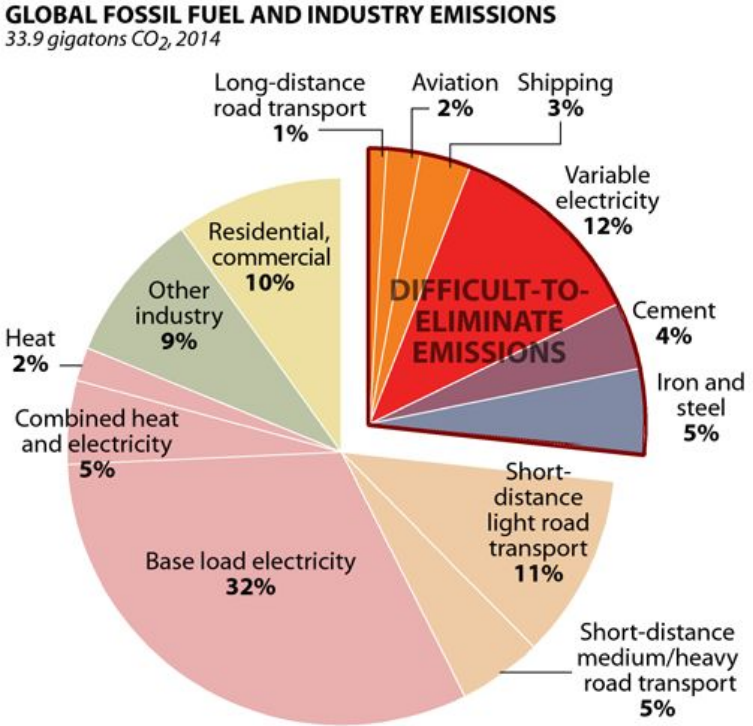

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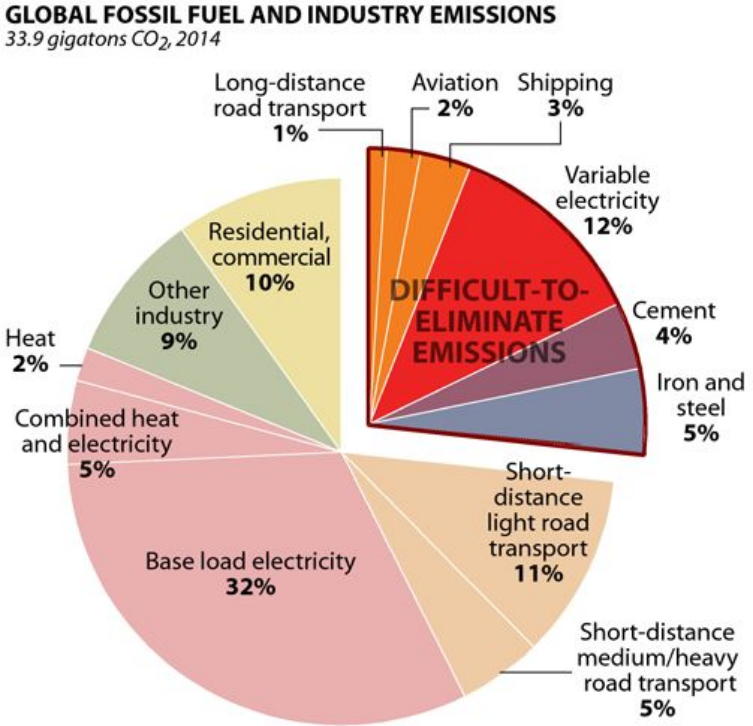

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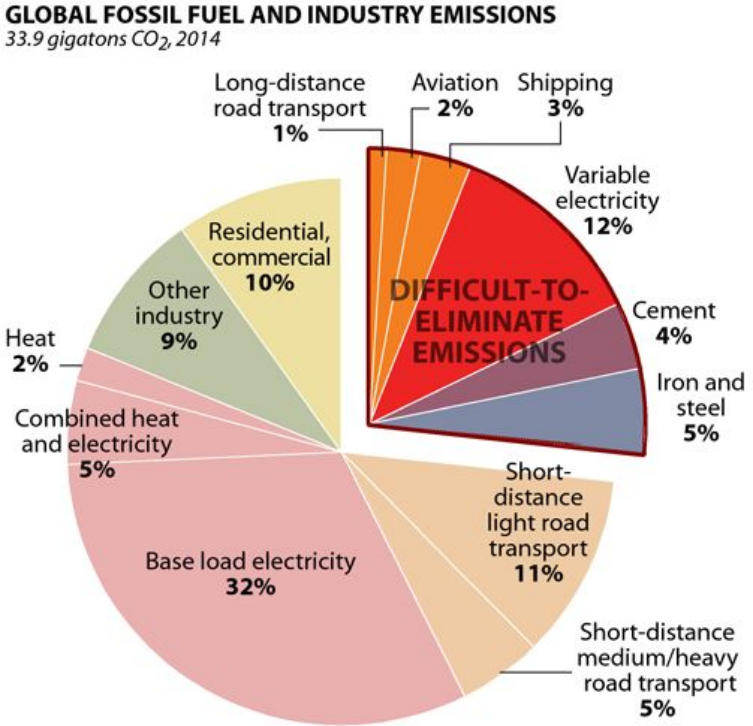

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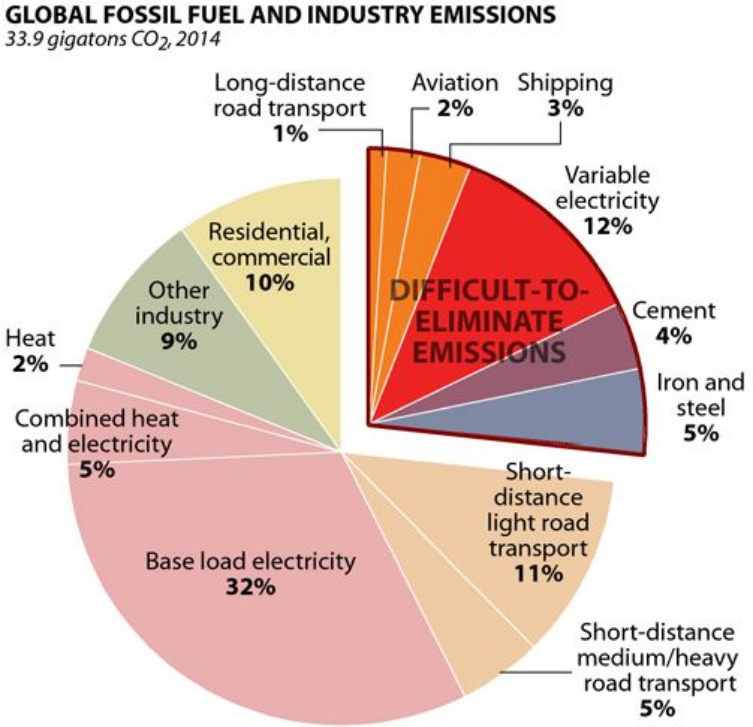
  - Long-haul transport
    - trucking, aviation, maritime fuel
  - Variable electricity
    - load-following power plants
  - Industrial emissions
    - mostly iron & cement



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Heavy Transport

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Heavy Transport

energy storage that is:

- cheap
- efficient
- lightweight

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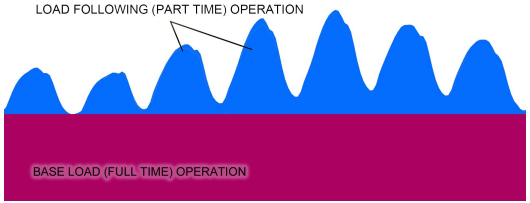

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Variable Electricity

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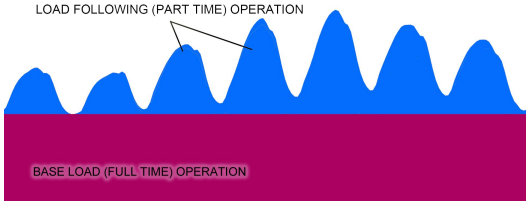

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Variable Electricity

power generation with:

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- grid compatibility
- low startup & shutdown costs

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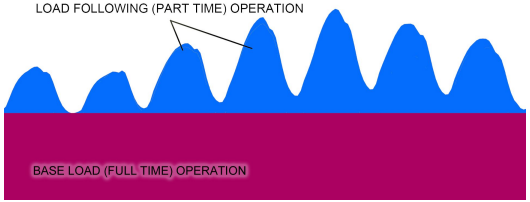

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Steel & Cement

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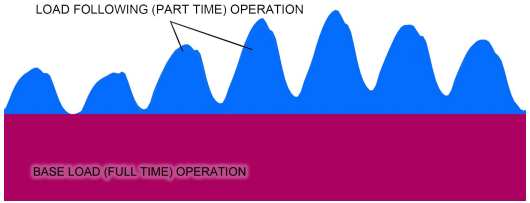

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industrial inputs that:

- produce high Ts
- are storable
- maintain steady-state operation

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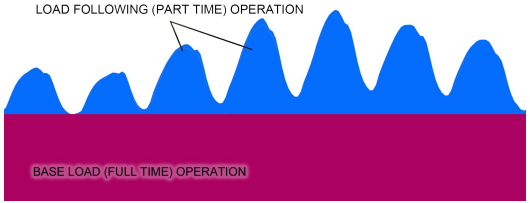

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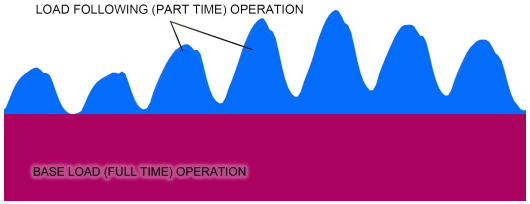
ENERGY DENSITY



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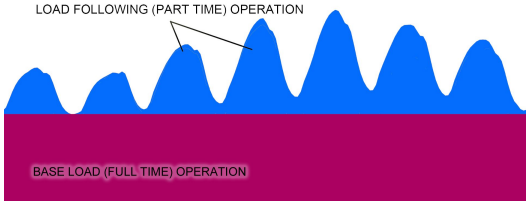

Heavy Transport

ENERGY DENSITY

Variable Electricity

FLEXIBILITY

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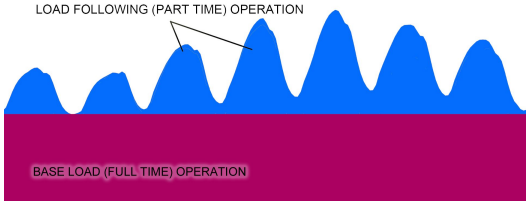


Heavy Transport

ENERGY DENSITY

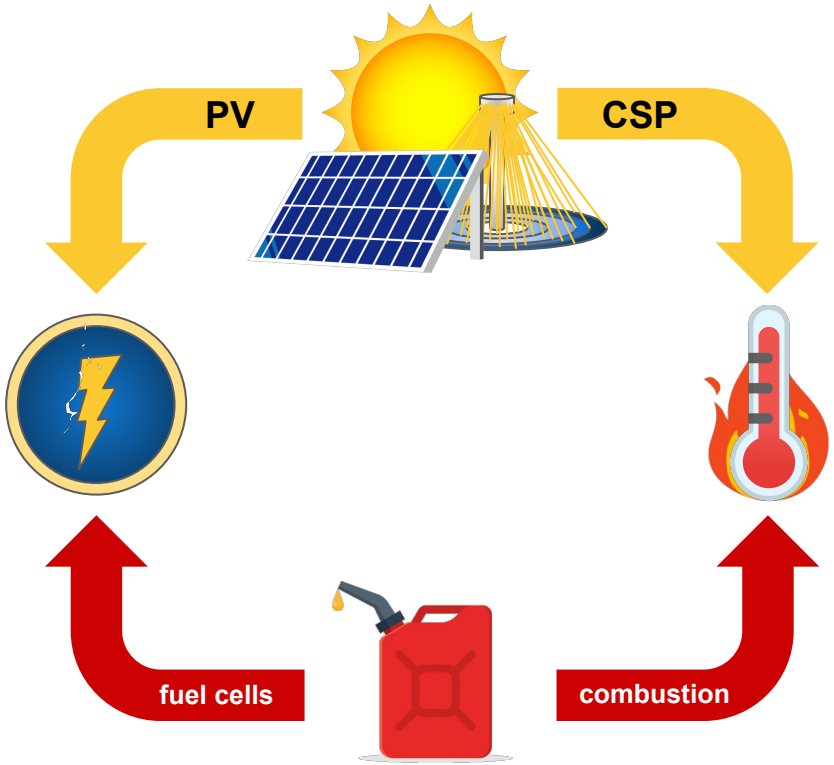
Variable Electricity

FLEXIBILITY

Steel & Cement

CHEMICAL POTENTIAL

Solar power isn’t built for this.



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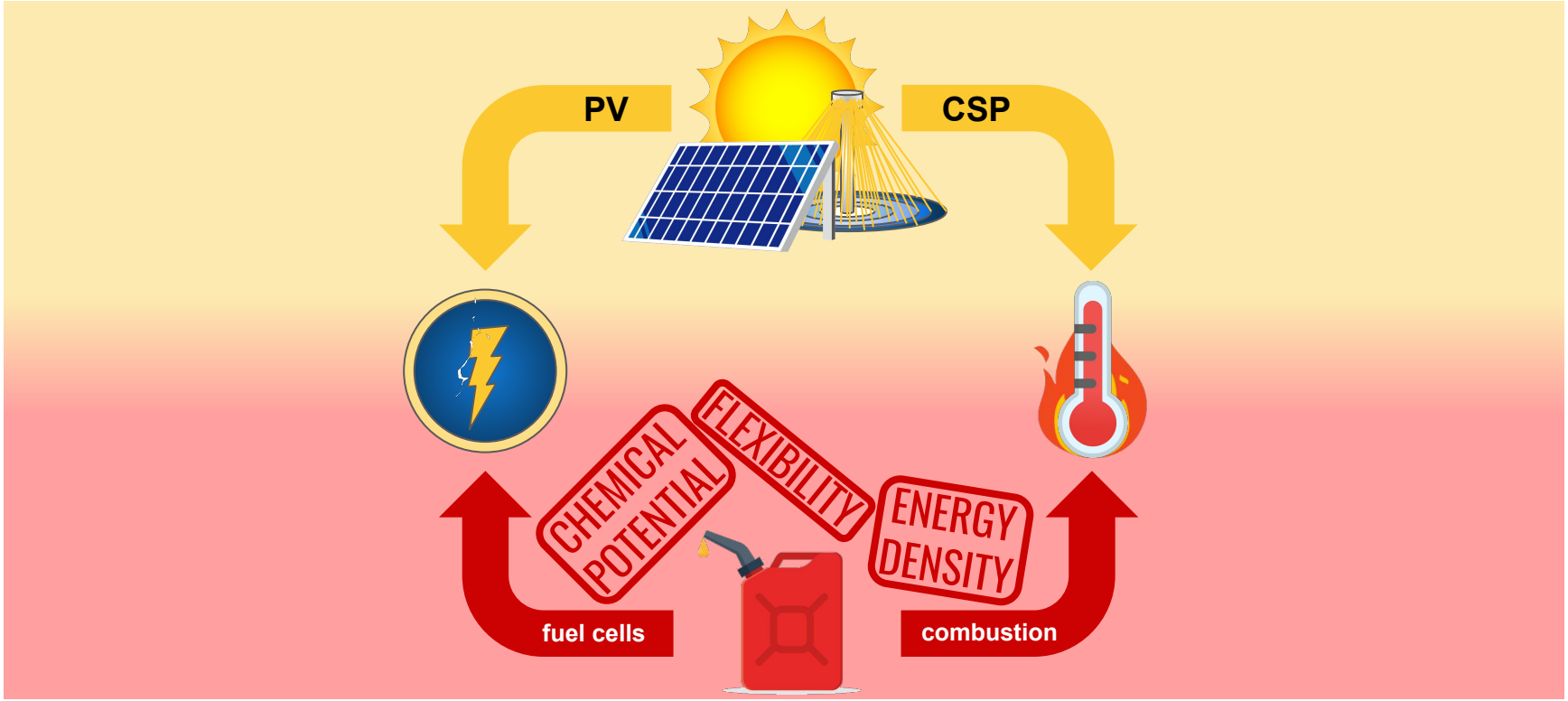

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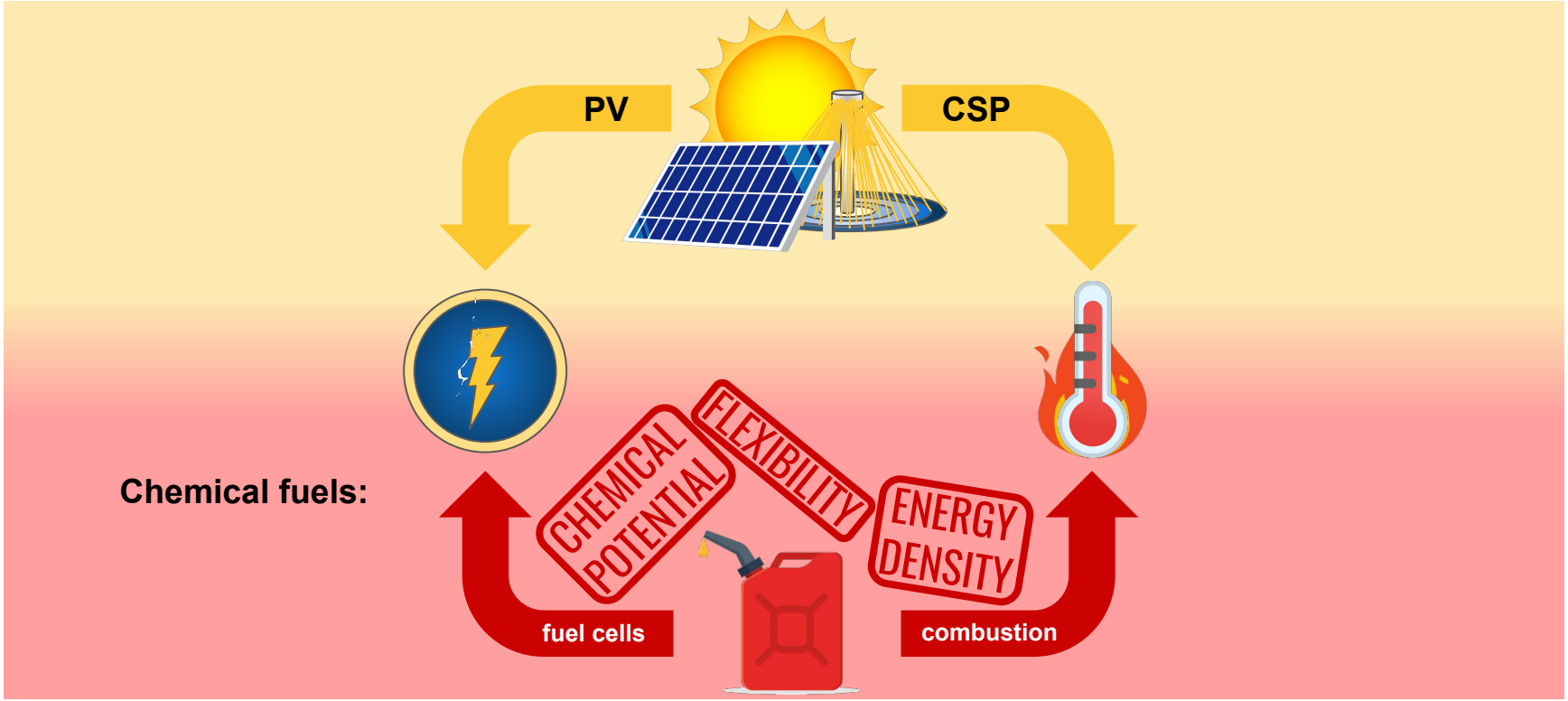

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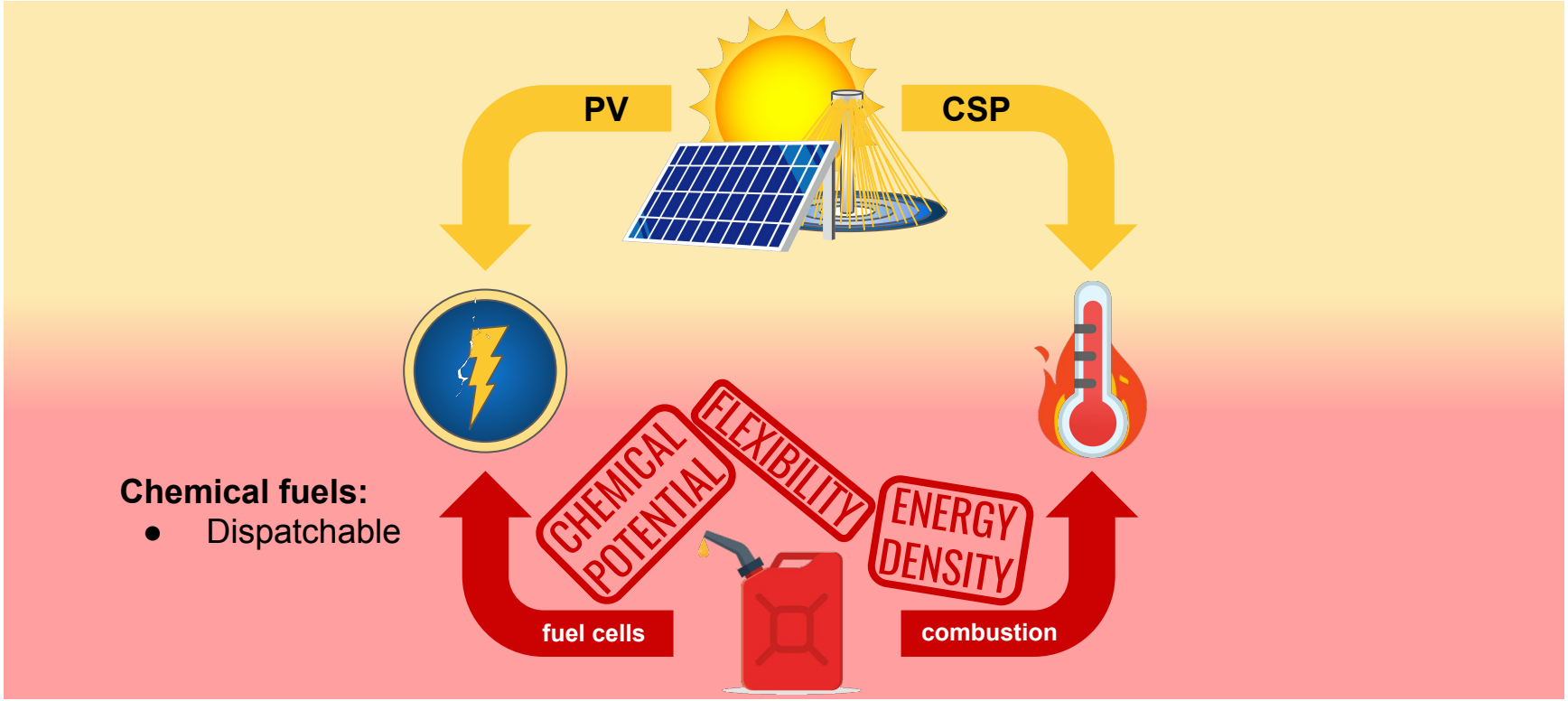

Chemical fuels:

- Dispatchable

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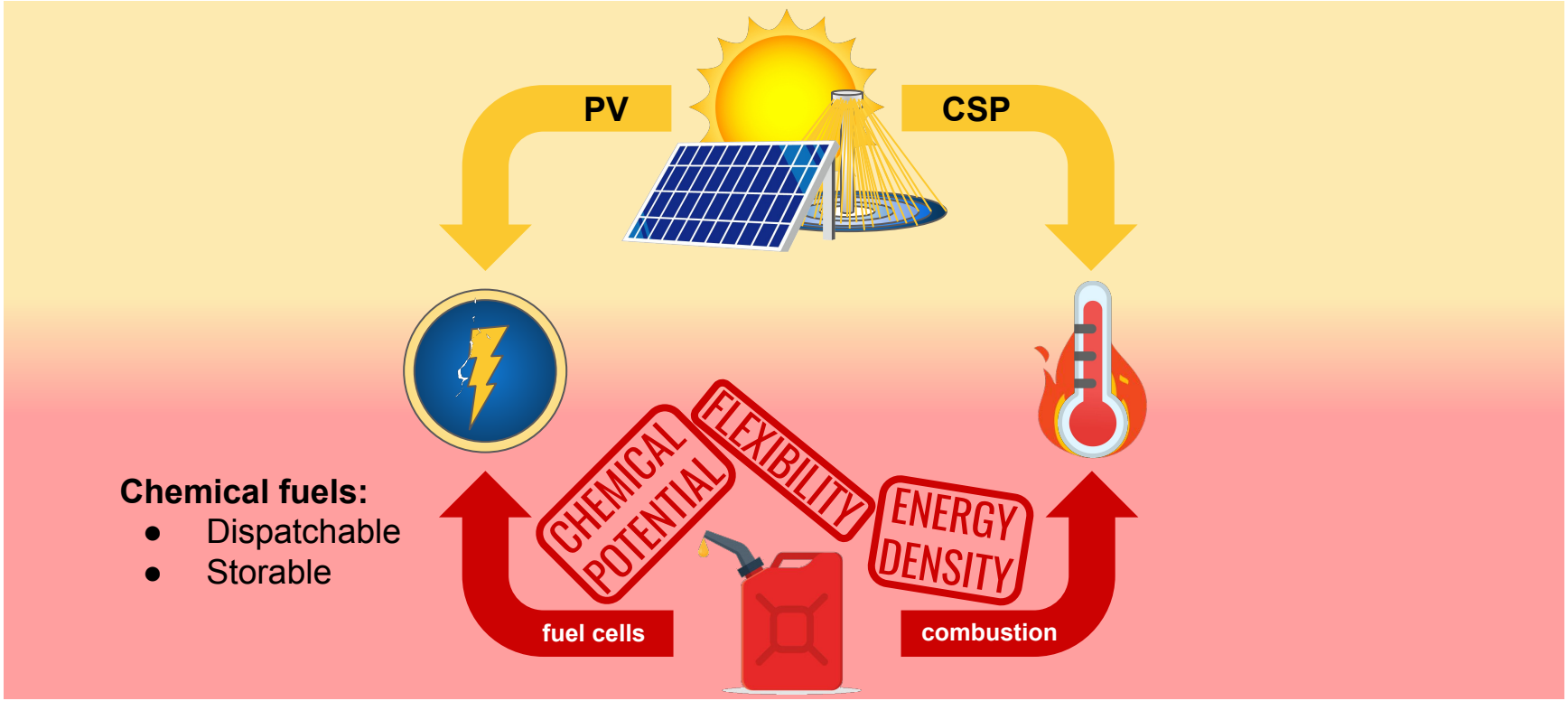

Chemical fuels:

- Dispatchable
- Storable

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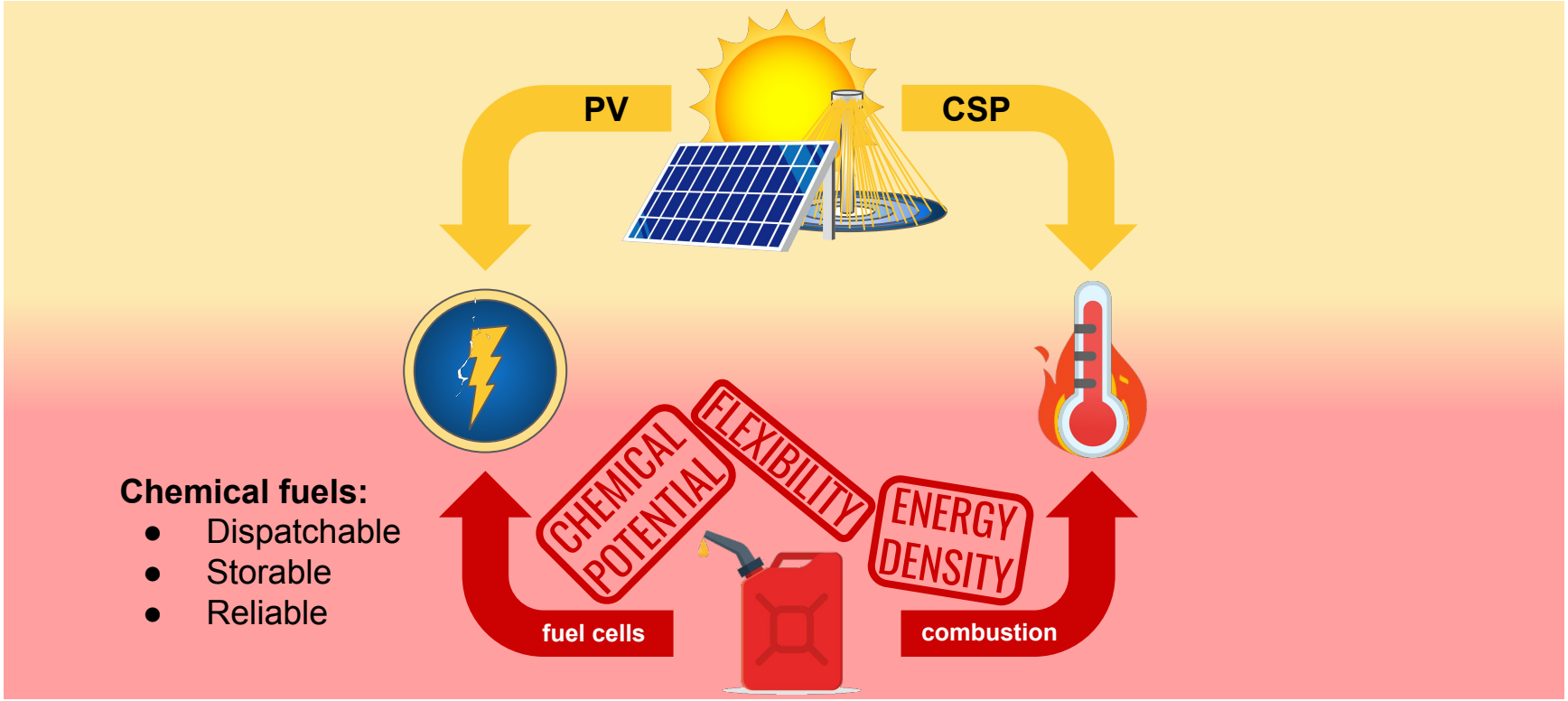

Chemical fuels:

- Dispatchable
- Storable
- Reliable

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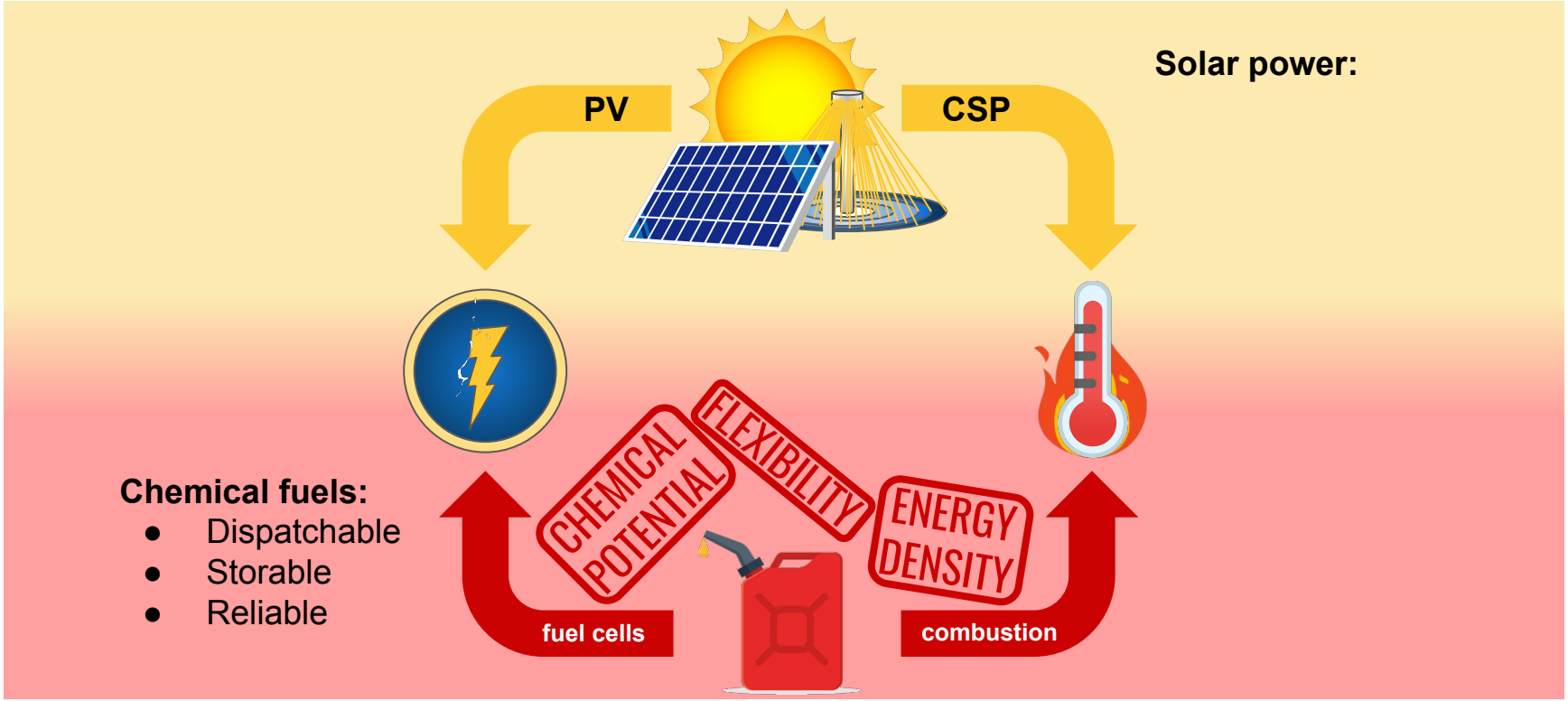

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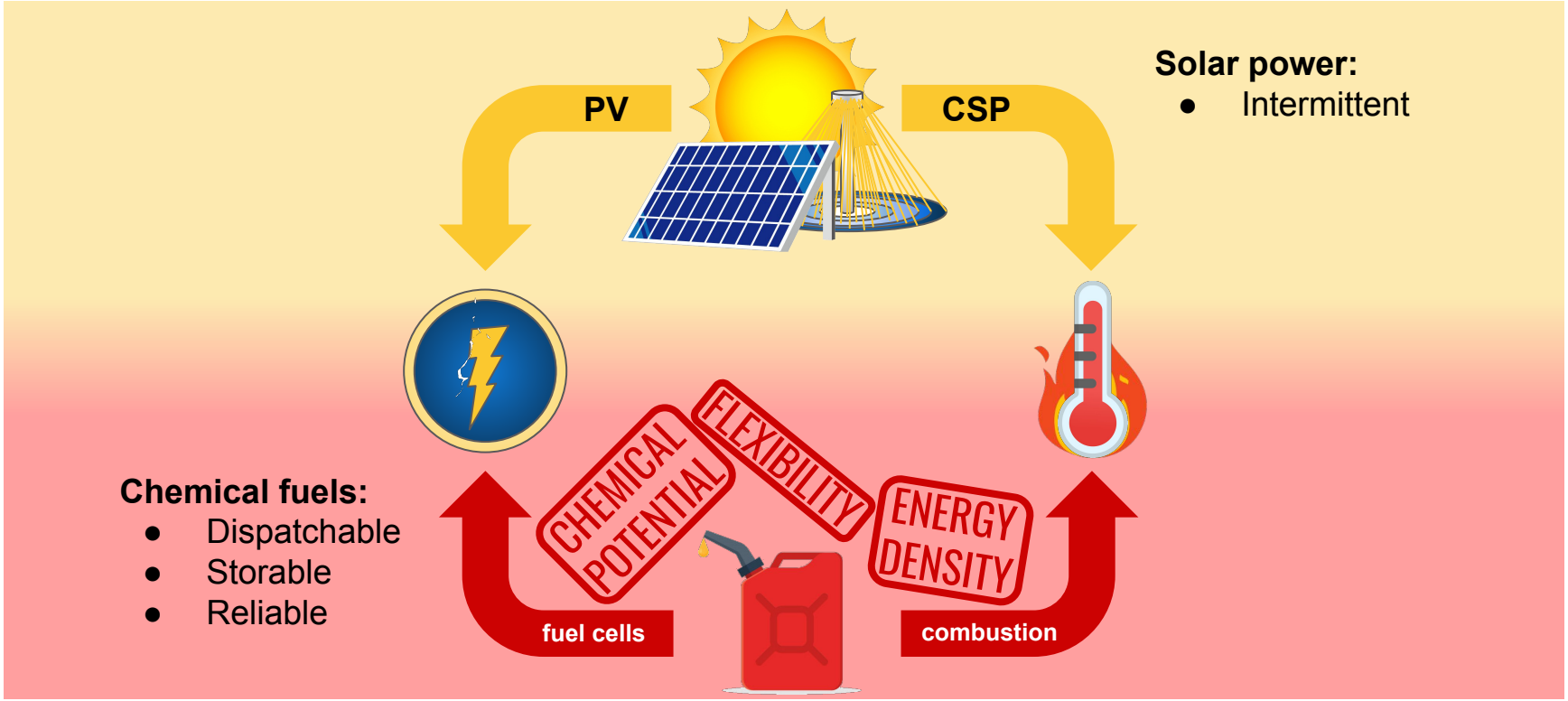

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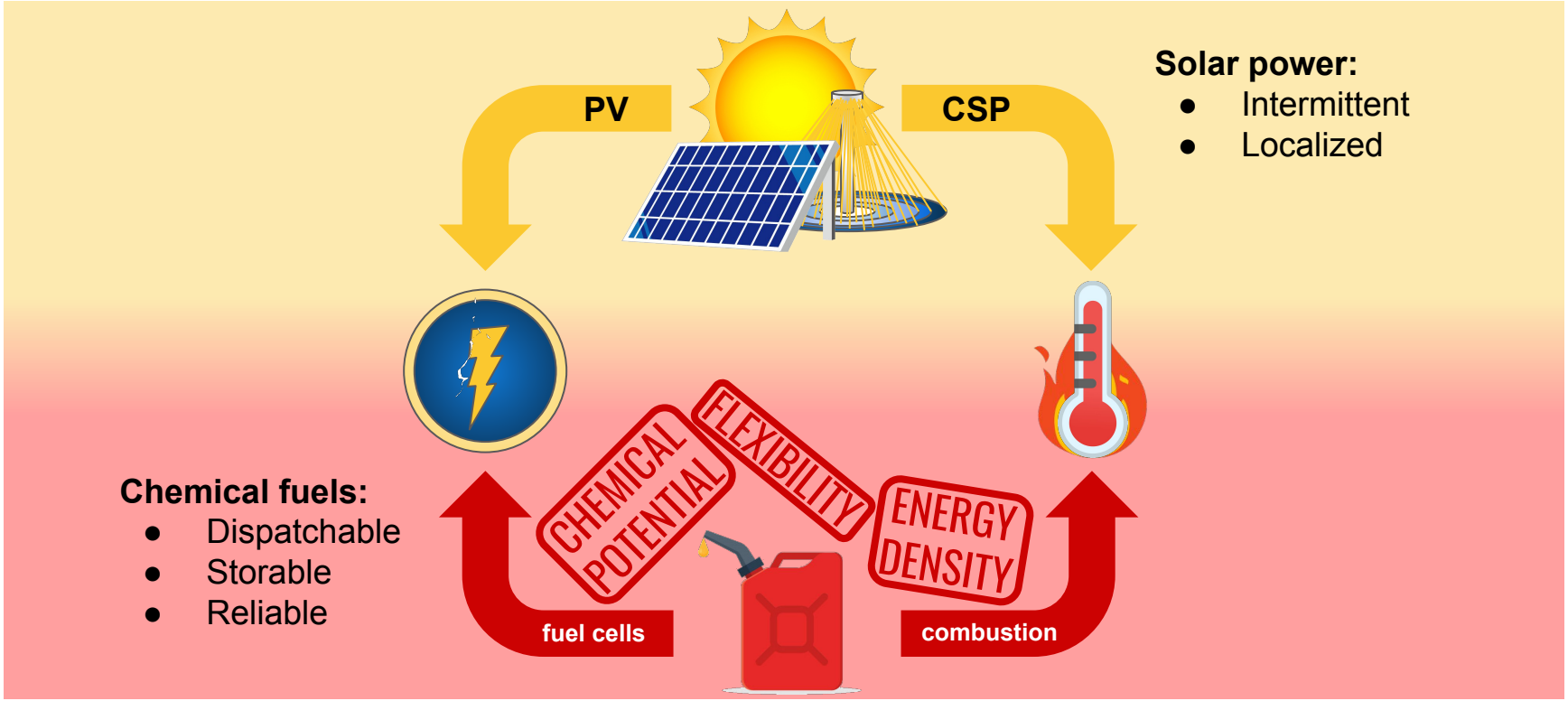

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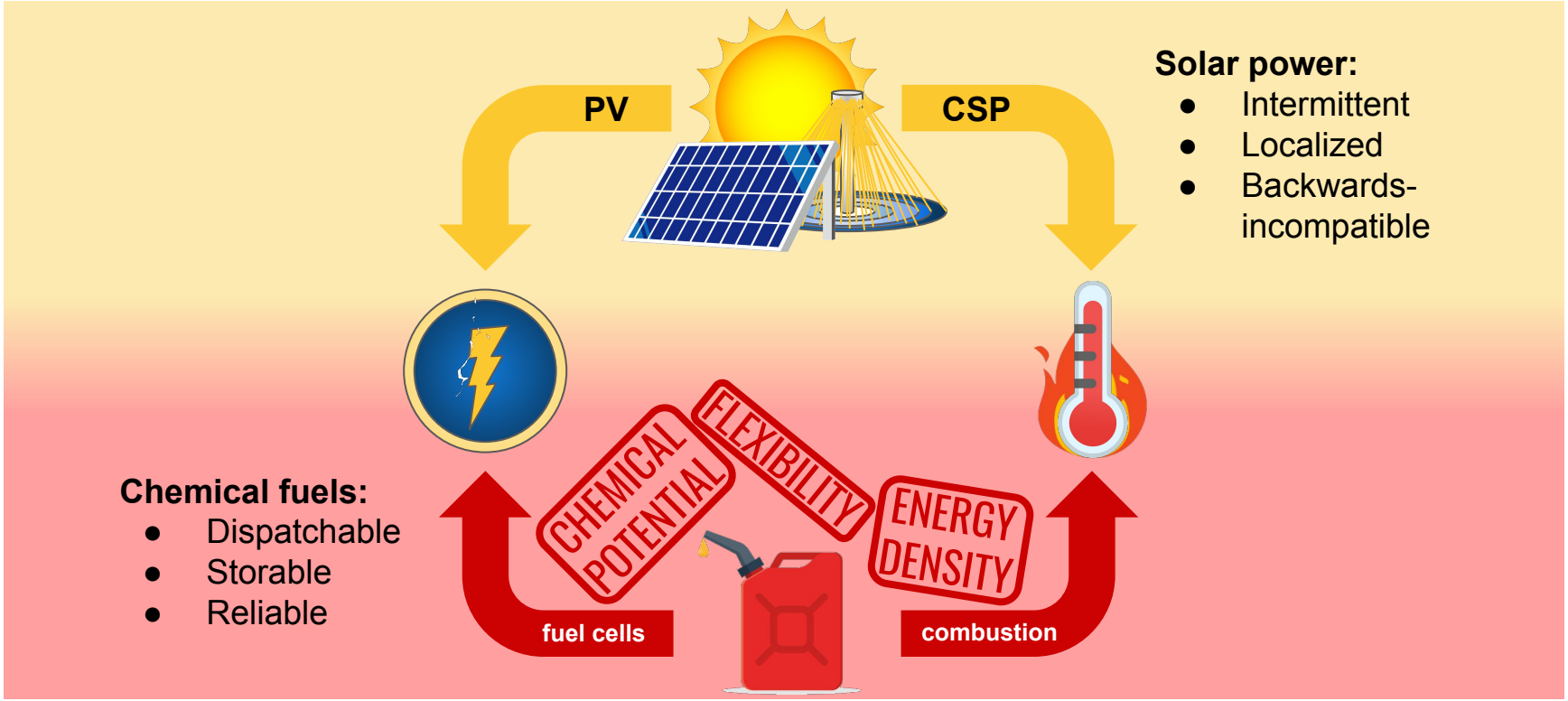

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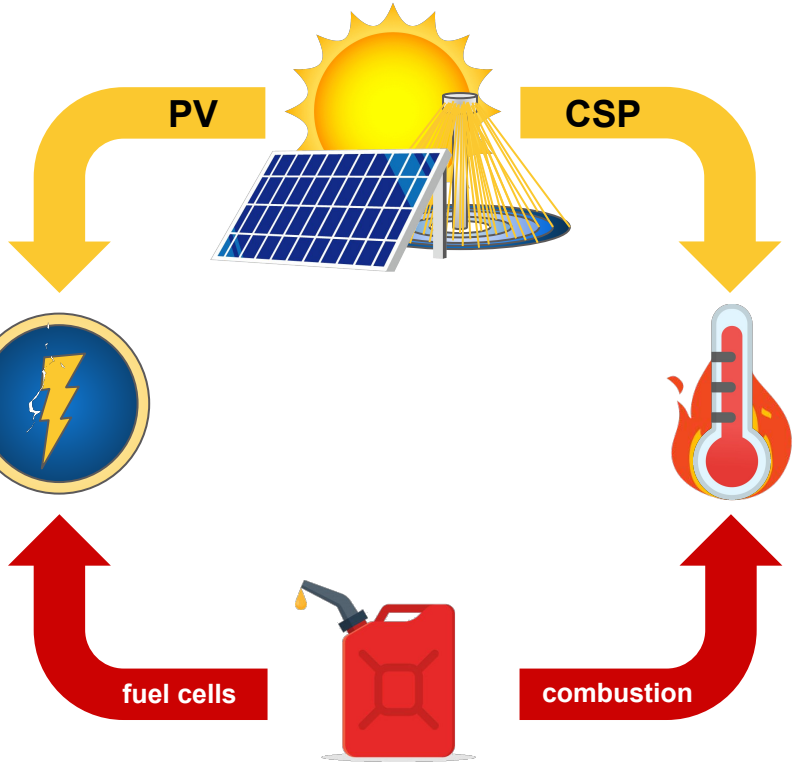

Solar power:

- Intermittent
- Localized
- Backwards-incompatible

Chemical fuels:

- Dispatchable
- Storable
- Reliable

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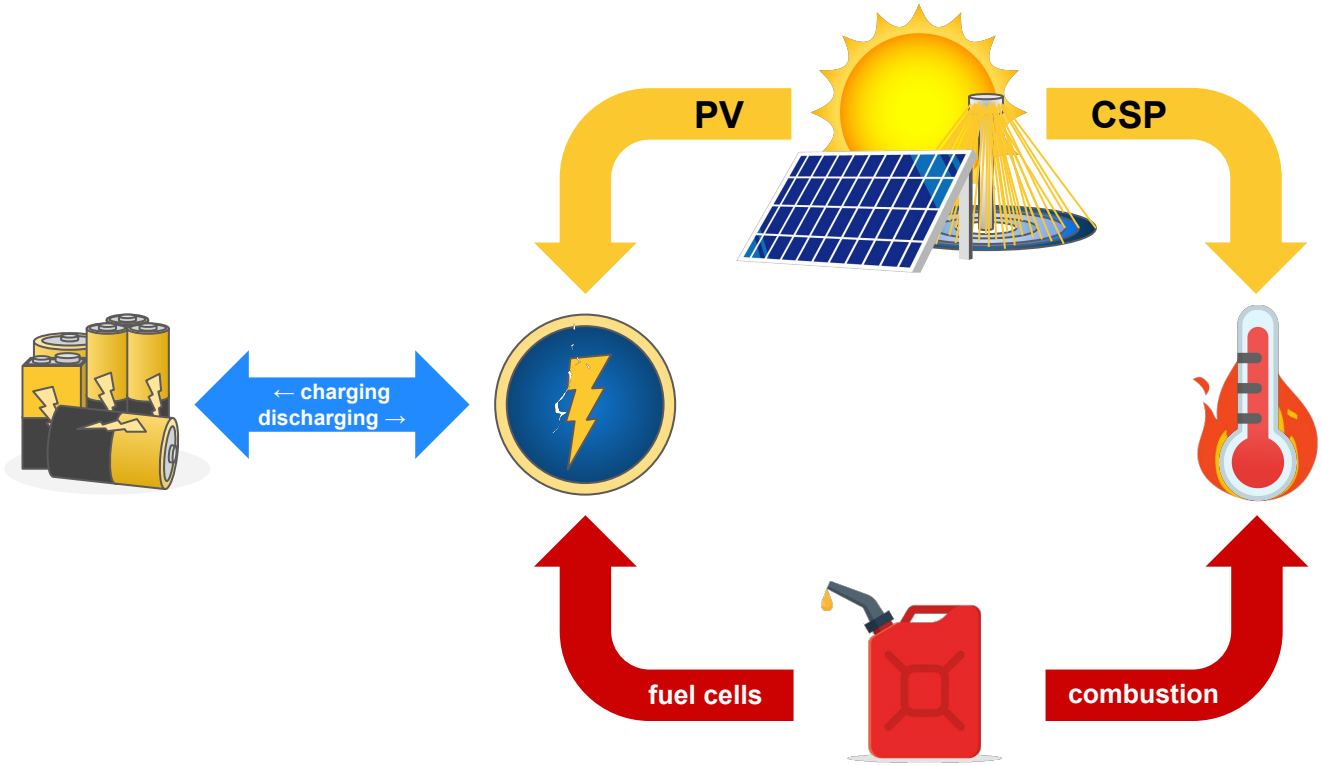

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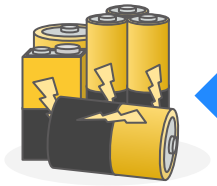

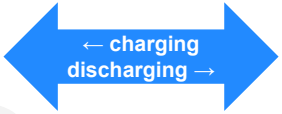

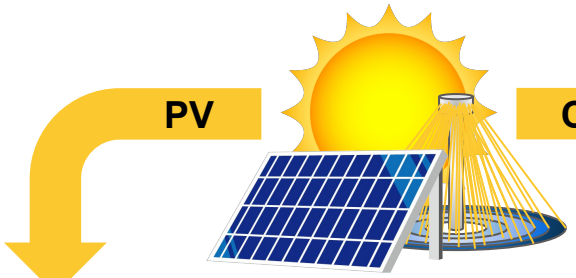

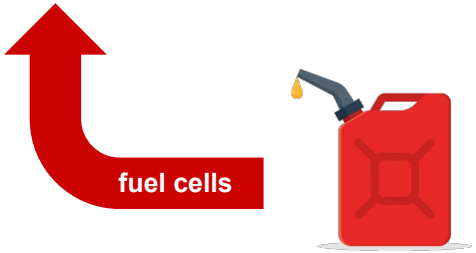

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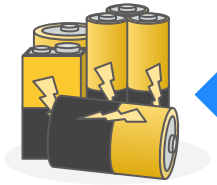
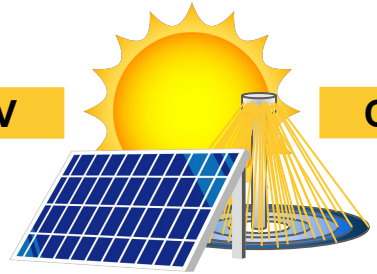


← charging
discharging →

PV



CSP

fuel cells

combustion

Batteries:

- Low energy density
- Aging / self-discharge
- Rare elements / conflict resources

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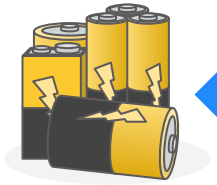

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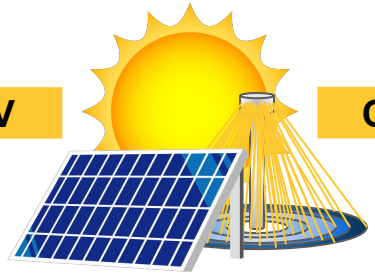

heat exchange→
←also heat exchange

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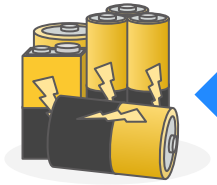

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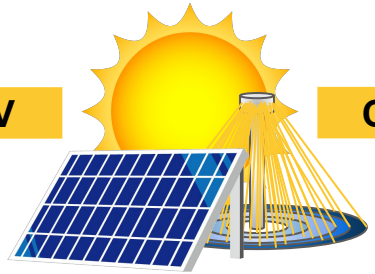

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Batteries:

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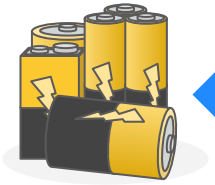
TES:

- Difficult to transport
- Low maximum T
- High capital costs / large minimum scale

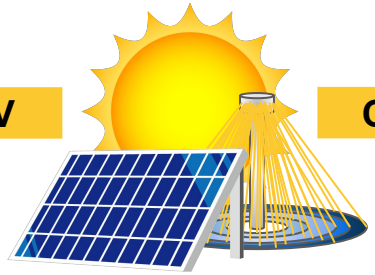
Solar power isn't built for this.



← charging
discharging →

PV

CSP



heat exchange→
←also heat exchange

fuel cells

combustion

Batteries:

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- Difficult to transport
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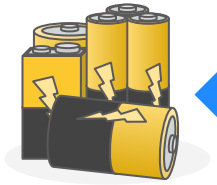

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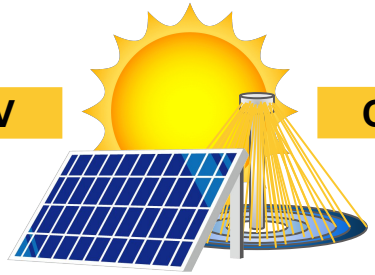

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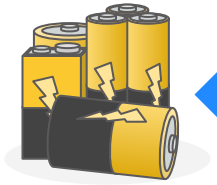

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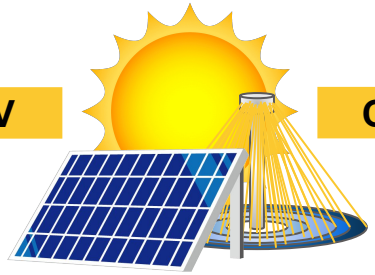

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Batteries/TES can’t beat chemical fuels

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iPhone 12

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Screen 6.1 inches
Height 5.78 inches (146.7mm)
Width 2.82 inches (71.5mm)

(146.7 × 71.5 × 7.4) mm^3 = 78 mL

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Appl. Energy **2013,** *103, 256.*
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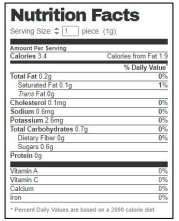

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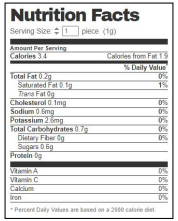

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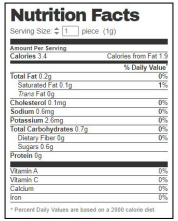

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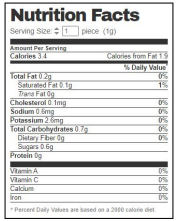

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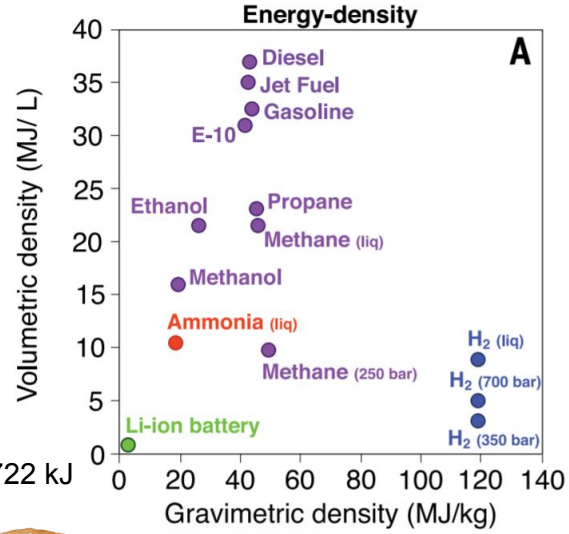

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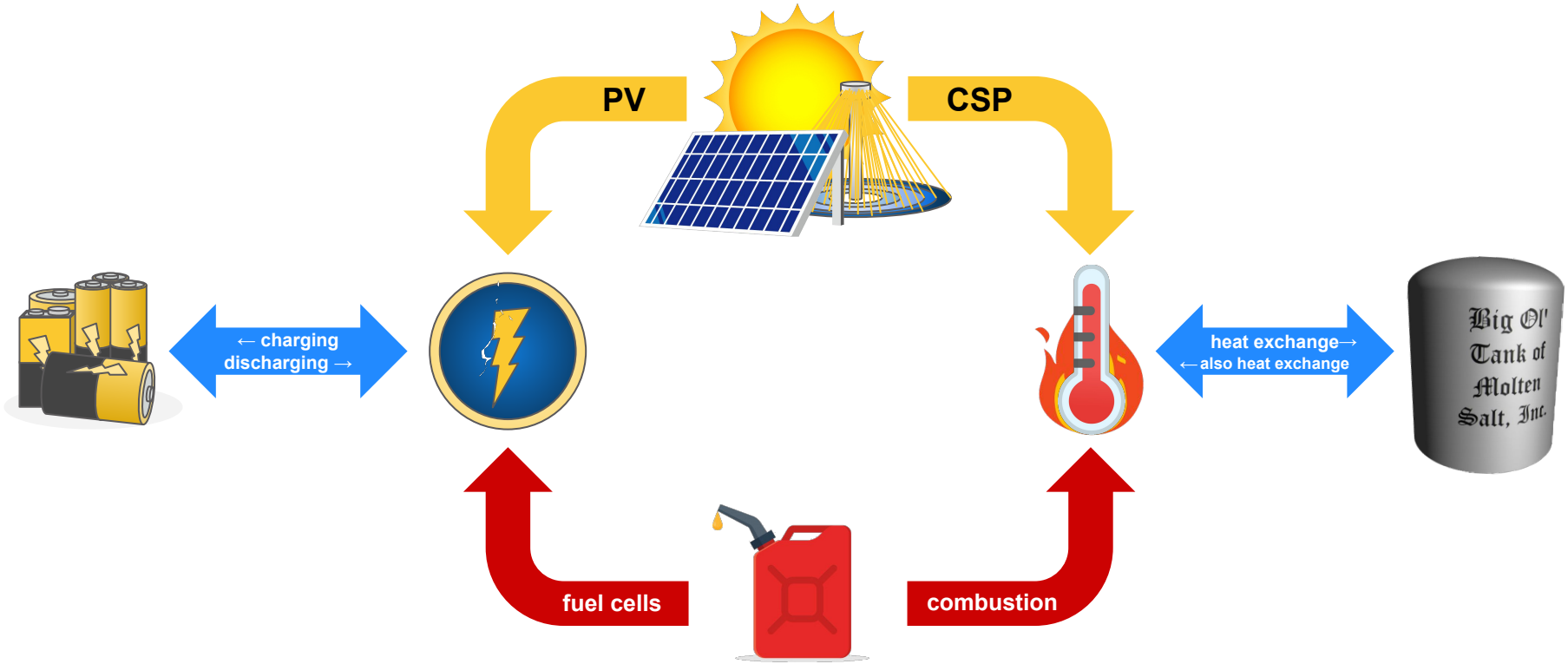
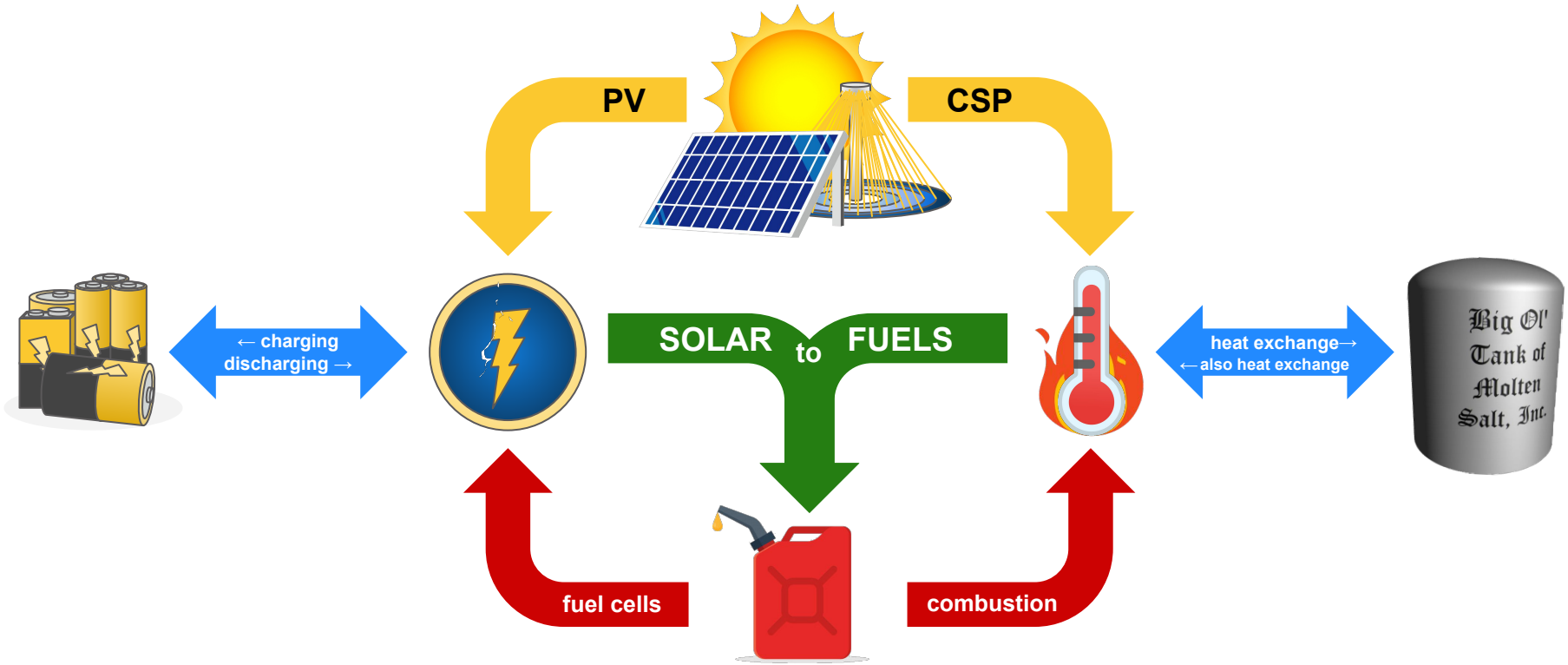
What does this mean for solar?



If you can't beat 'em, join 'em



What fuels should be solarized?

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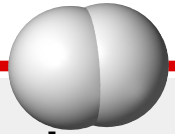
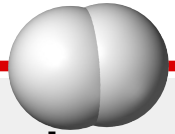


Hydrogen

What fuels should be solarized?



Hydrogen

+ great gravimetric energy density

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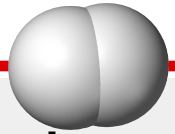

Hydrogen

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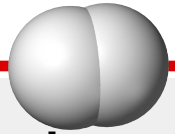

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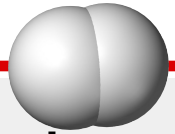

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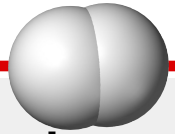

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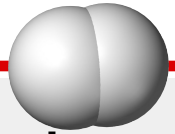

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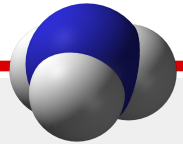
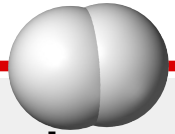


Ammonia

What fuels should be solarized?



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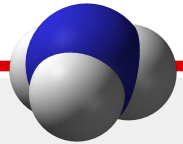

Ammonia

+ zero-carbon hydrogen storage

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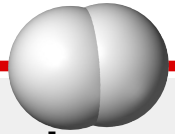

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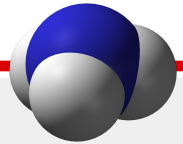

Ammonia

+ zero-carbon hydrogen storage
+ fairly easy to liquify or chemisorb

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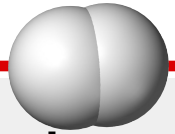

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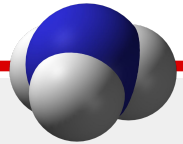

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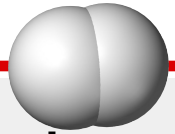

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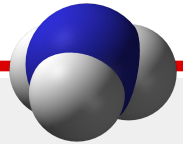

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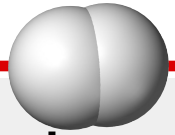

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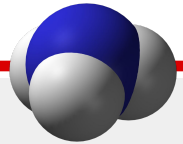

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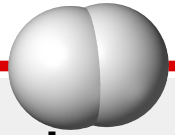

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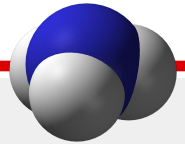

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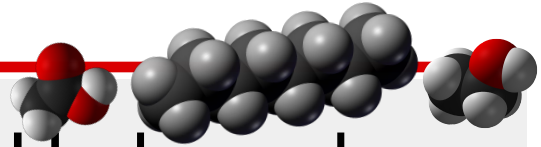
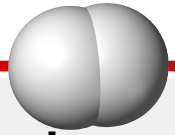


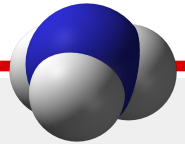
Hydrocarbons

What fuels should be solarized?



Hydrogen

+ great gravimetric energy density
+ feedstock for solar NH_3, C_n fuels
+ well-studied synthesis routes
− awful volumetric energy density
− expensive to compress/liquify



Ammonia

+ zero-carbon hydrogen storage
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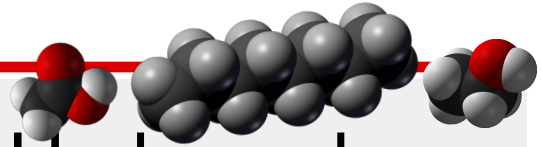

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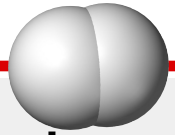

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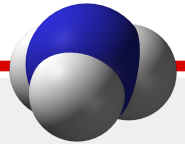

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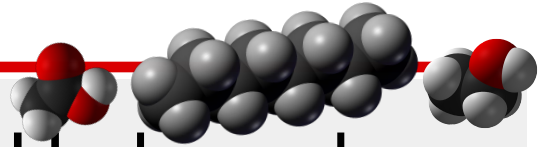

Hydrocarbons

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+ very easy to store and transport

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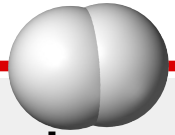

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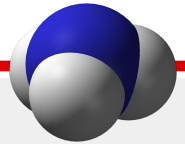

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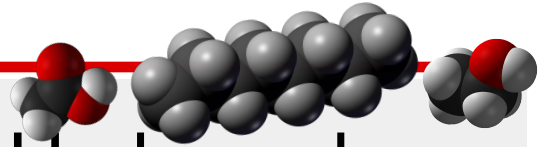

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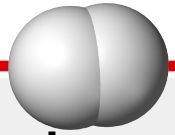

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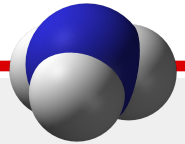

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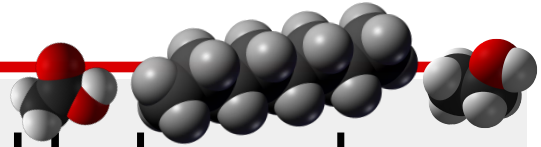
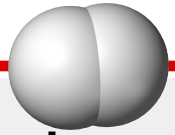


Hydrocarbons

+ high gravi/volumetric energy density
+ very easy to store and transport
+ compatible w/ legacy fossil infrastructure
− requires CCS for net zero emissions

What fuels should be solarized?



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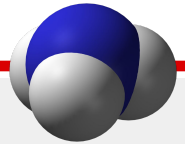

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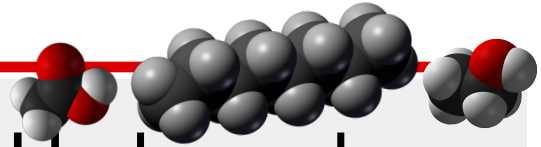
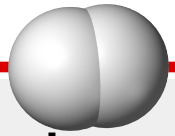


Hydrocarbons

+ high gravi/volumetric energy density
+ very easy to store and transport
+ compatible w/ legacy fossil infrastructure
− requires CCS for net zero emissions
− product selectivity can be challenging

What technologies do we need to do it?



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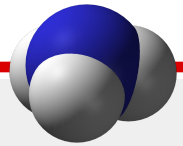

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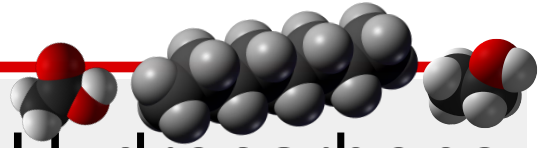

Hydrocarbons

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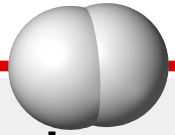
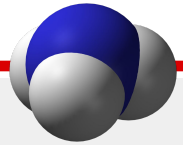


Hydrogen

- Low-temperature water splitting (LTE)



Ammonia

Hydrocarbons

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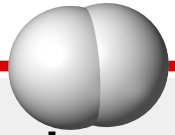

Hydrogen

- Low-temperature water splitting (LTE)
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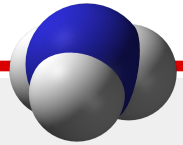

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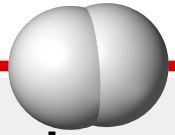

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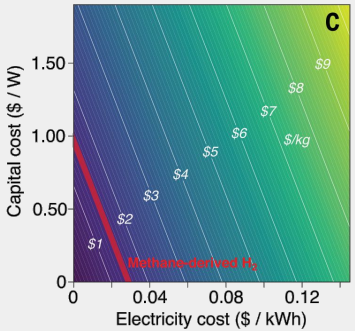

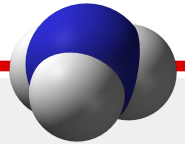

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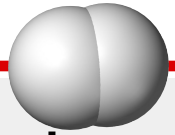

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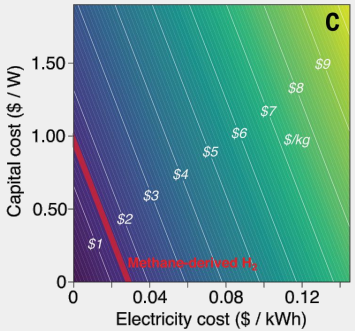

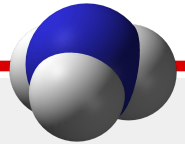

Ammonia

- Solar thermo / electrochemical nitrogen fixation

Hydrocarbons

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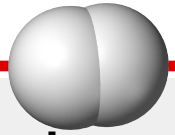

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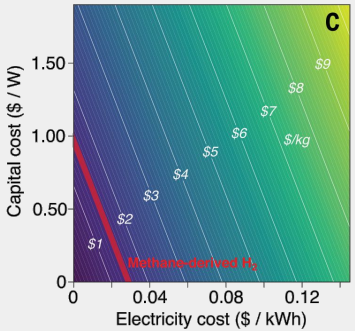

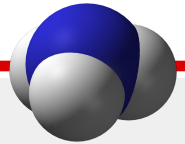

Ammonia

- Solar thermo / electrochemical nitrogen fixation
- Ammonia fuel cells / combustion engines / dissociation reactors

Hydrocarbons

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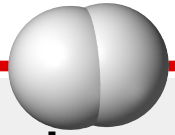

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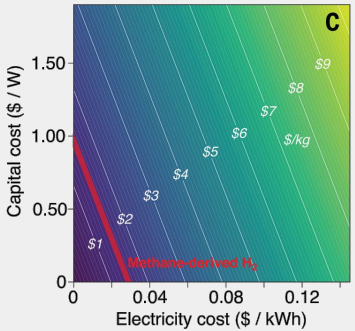

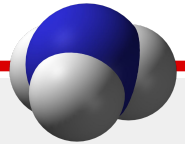

Ammonia

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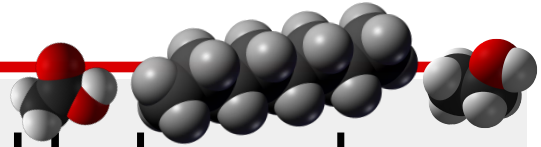

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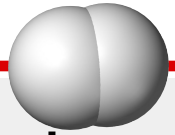

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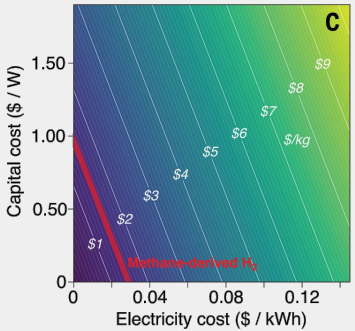

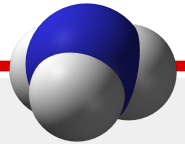

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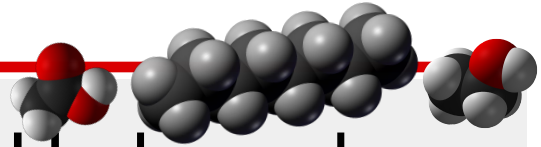

Hydrocarbons

- Solar thermo / photo / electrochemical CO_2 reduction

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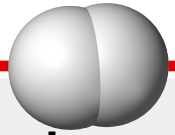

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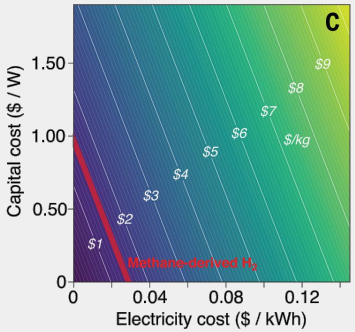

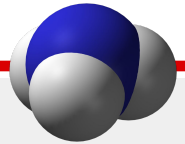

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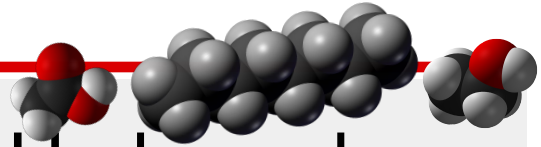

Hydrocarbons

- Solar thermo / photo / electrochemical CO_2 reduction
- Selective & efficient carbon upgrading catalysts ($C_1 \rightarrow C_n$)

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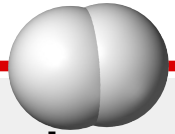

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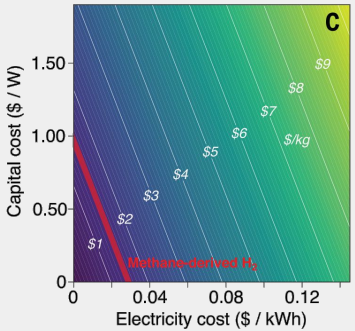

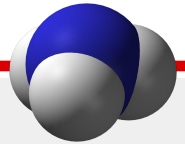

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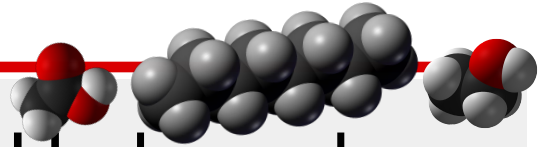

Hydrocarbons

- Solar thermo / photo / electrochemical CO_2 reduction
- Selective & efficient carbon upgrading catalysts ($C_1 \rightarrow C_n$)
- Cost-effective carbon capture sorbents 😔

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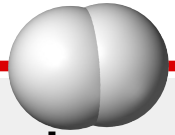
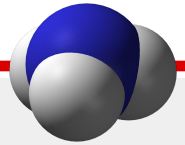
What technologies do we need to do it?



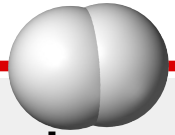
Hydrogen



Ammonia

Hydrocarbons

What technologies do we need to do it?



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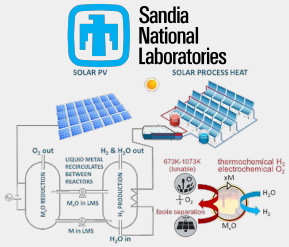
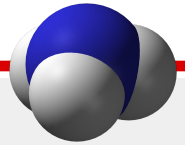


Solar Hydrogen from Water Splitting using Liquid Metal Redox Cycles Promoted by Electrochemistry



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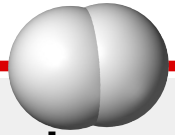

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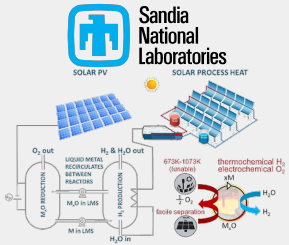

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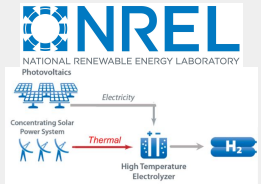

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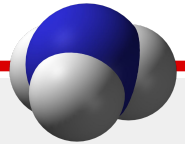

Ammonia

Hydrocarbons

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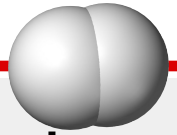
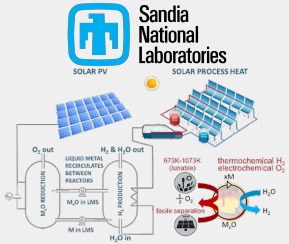


Hydrogen



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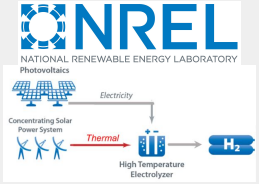

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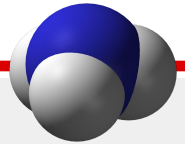

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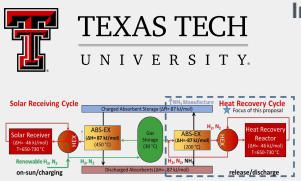
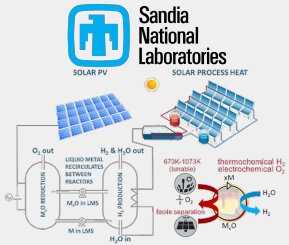


Intensified Ammonia Solar Reactor for Green Ammonia Manufacture and Gen3 Thermochemical Energy Storage

Hydrocarbons

What technologies do we need to do it?

Hydrogen



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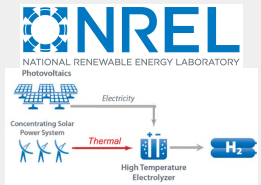

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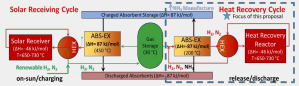
Ammonia

TEXAS TECH UNIVERSITY



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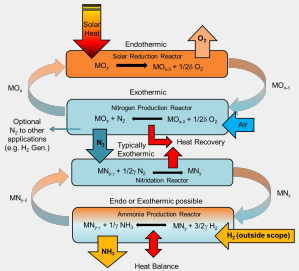


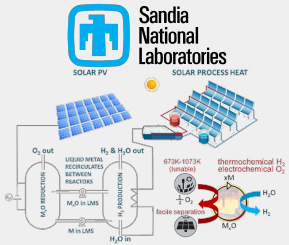
Sandia National Laboratories

Solar Thermochemical Ammonia Production (STAP)

Hydrocarbons

What technologies do we need to do it?

Hydrogen



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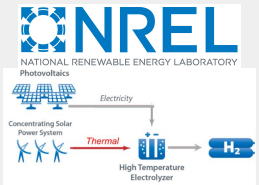

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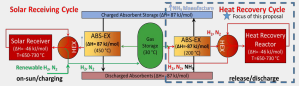

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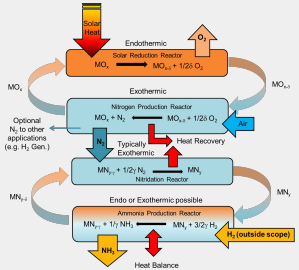

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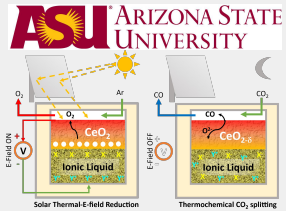
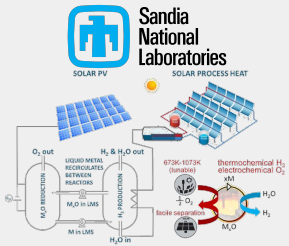


Concentrated Solar Thermal Fuels Production by Electric Field Enhanced Two-Step CO_2 Splitting

What technologies do we need to do it?

Hydrogen



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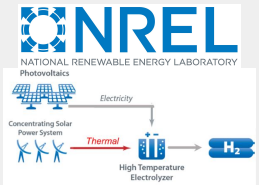

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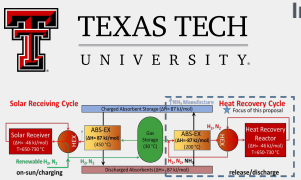

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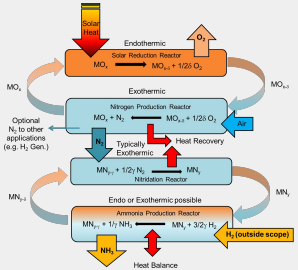

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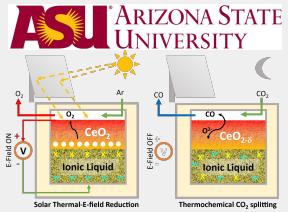

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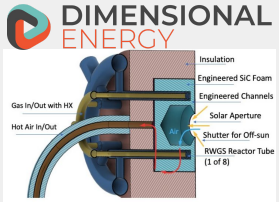

SiC Receiver/Reactor by Additive Manufacturing for Concentrated Solar Thermocatalysis with Thermal Energy Storage

The Pitch: Dedicated Solar Fuels FOA

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- Consolidate projects under a single umbrella

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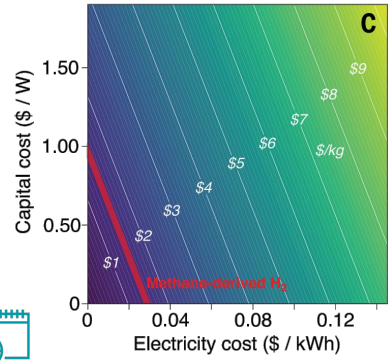

The Pitch: Dedicated Solar Fuels FOA

- Consolidate projects under a single umbrella
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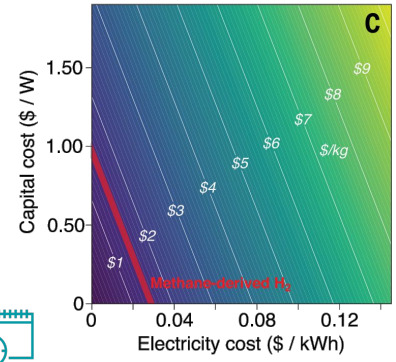
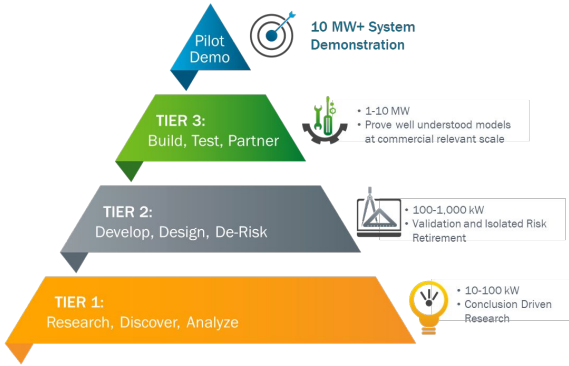
- Scale & advance solar fuels synthesis to demonstration-scale pilot projects





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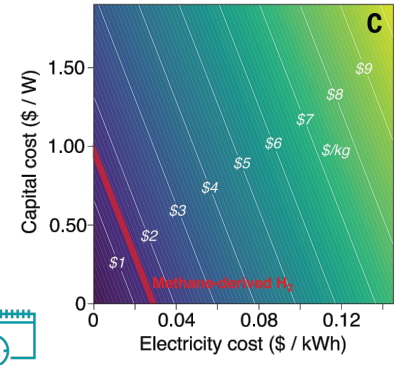

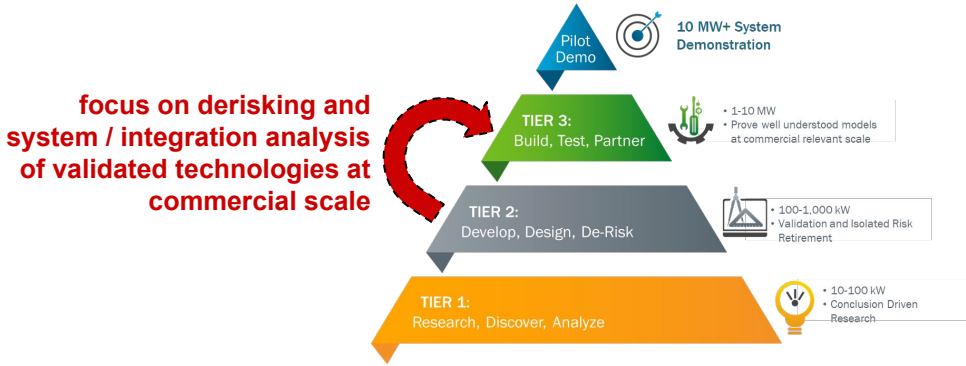

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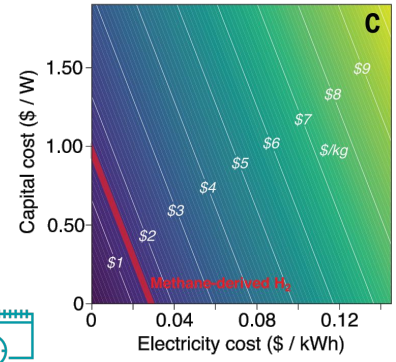

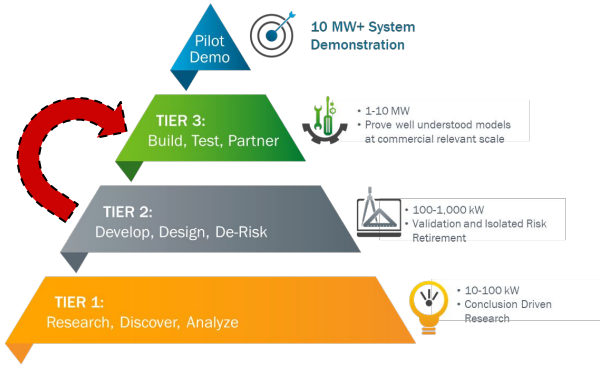

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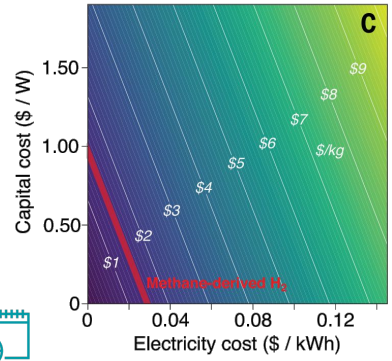

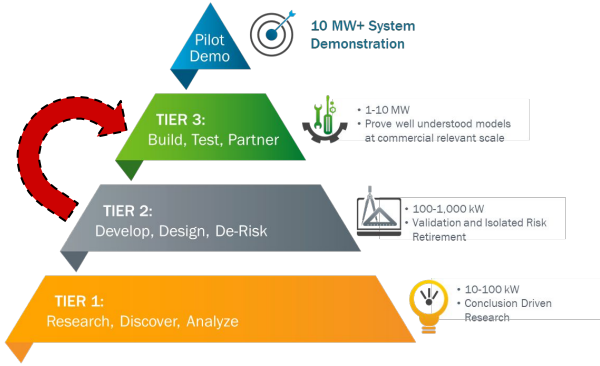

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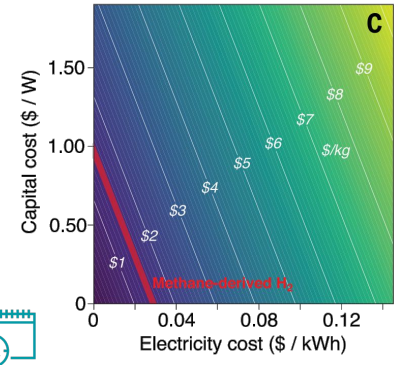

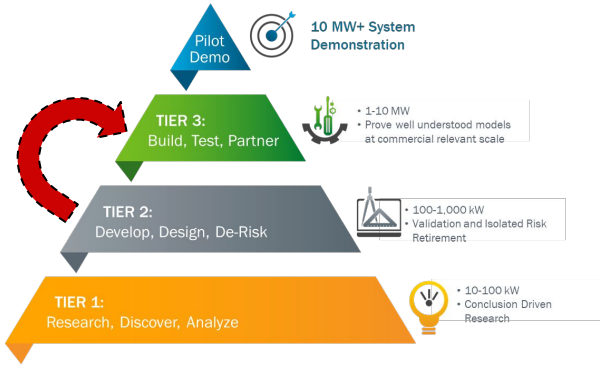

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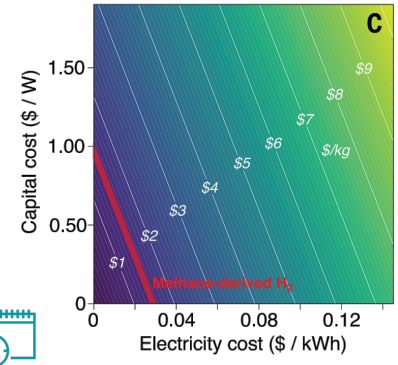

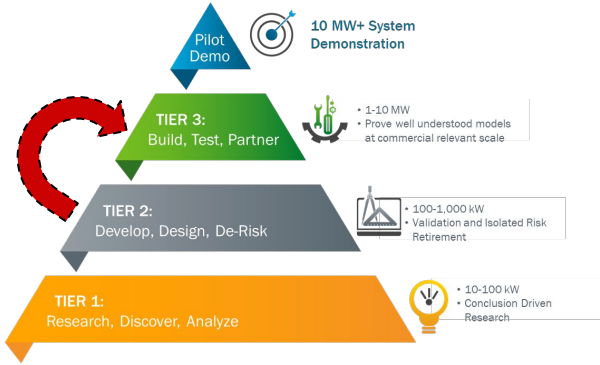

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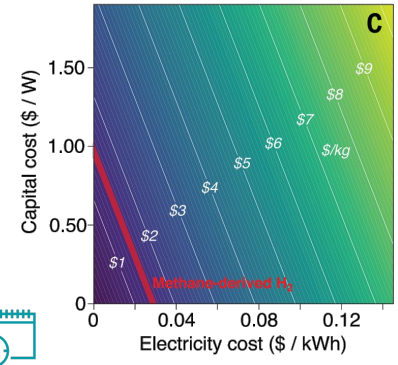

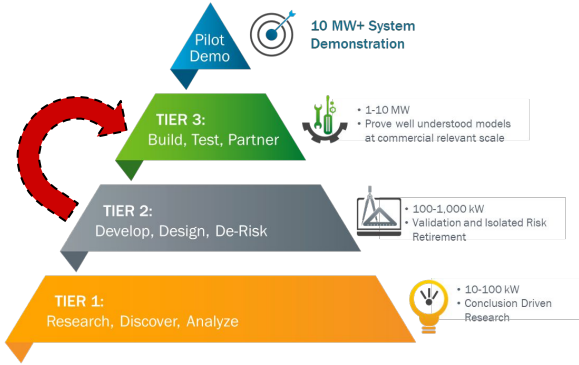

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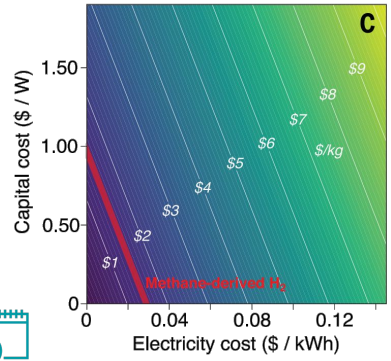
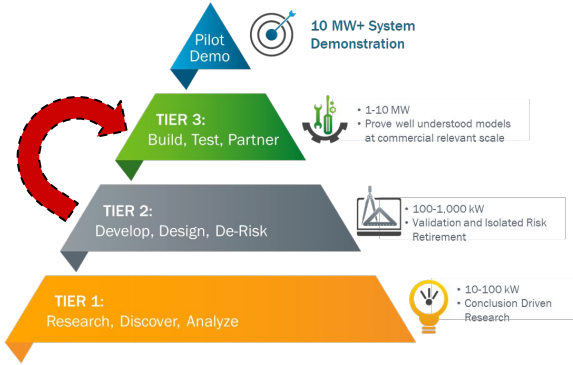
  - Energy interconversion efficiency: **>95%**
  - Valuable hydrocarbon selectivity: **>56%**





Hypothetical Solar Fuels Utopias

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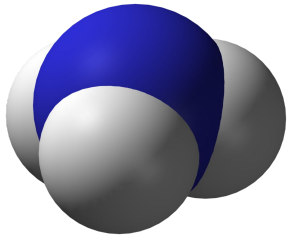
- Ammonia for zero-carbon heavy transport:



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Hypothetical Solar Fuels Utopias

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Hypothetical Solar Fuels Utopias

- Ammonia for zero-carbon heavy transport:
  - Synthesize NH_3 from air + green H_2 using PV/CSP on solid-oxide catalysts
  - Safely/reversibly store / transport NH_3 as absorbed $[Mg,Ca]Cl_2$ ammine salt complexes

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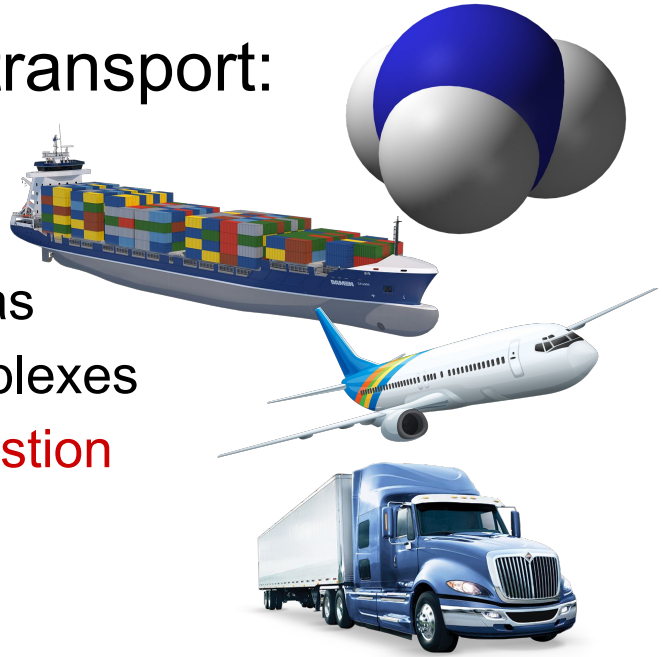
  - Safely/reversibly store / transport NH_3 as absorbed $[Mg,Ca]Cl_2$ ammine salt complexes
  - Fuel cells and engines for direct combustion

$$\mathbf{2\ NH_3 + 3/2\ O_2 \rightarrow N_2 + 3\ H_2O}$$



J. Mater. Chem. **2008**, *18*, 2304.
Int. J. Hydrog. Energy **2012**, *37*, 1482.
Int. J. Hydrog. Energy **2019**, *44*, 3680.
Energies **2020**, *13*, 3062.
Front. Energy Res. **2021**, *9*, 580808.

Hypothetical Solar Fuels Utopias

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    $2\ NH_3 + 3/2\ O_2 \rightarrow N_2 + 3\ H_2O$
  - Decarbonize the entire fertilizer industry (~1.4% of global emissions) while we're at it

J. Mater. Chem. **2008**, *18*, 2304.
Int. J. Hydrog. Energy **2012**, *37*, 1482.
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Hypothetical Solar Fuels Utopias

Hypothetical Solar Fuels Utopias

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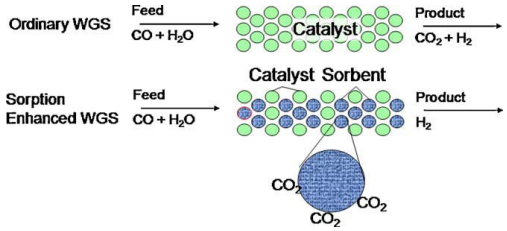

Science **2010**, *330*, 1797.
Int. J. Greenh. Gas Control **2011**, *5*, 200.
React. Chem. Eng. **2019**, *4*, 1431.
J. Electrochem. Soc. **2020**, *167*, 044508.
ACS Catal. **2021**, *11*, 1613.

Hypothetical Solar Fuels Utopias

- Sorption-enhanced iron production:
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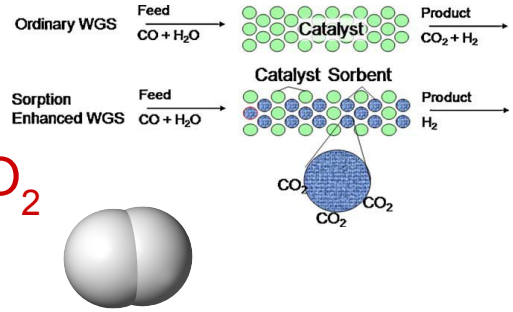
$$CO + H_2O \rightarrow H_2 + CO_2^{(captured)}$$



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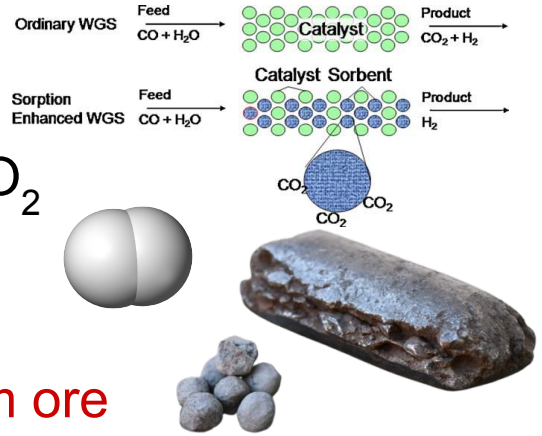

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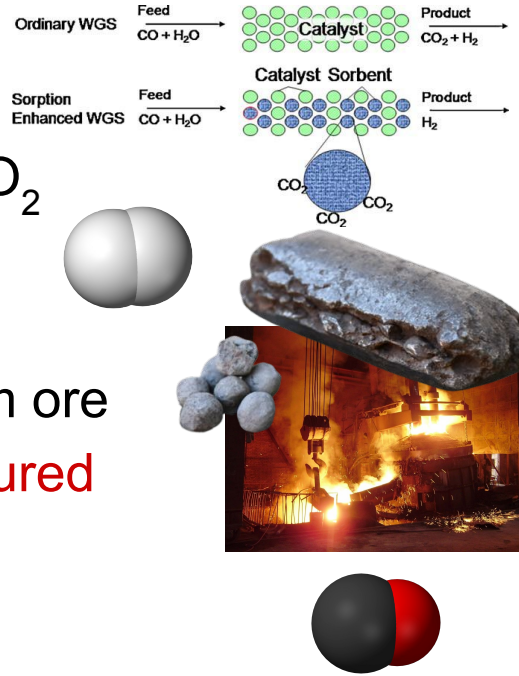

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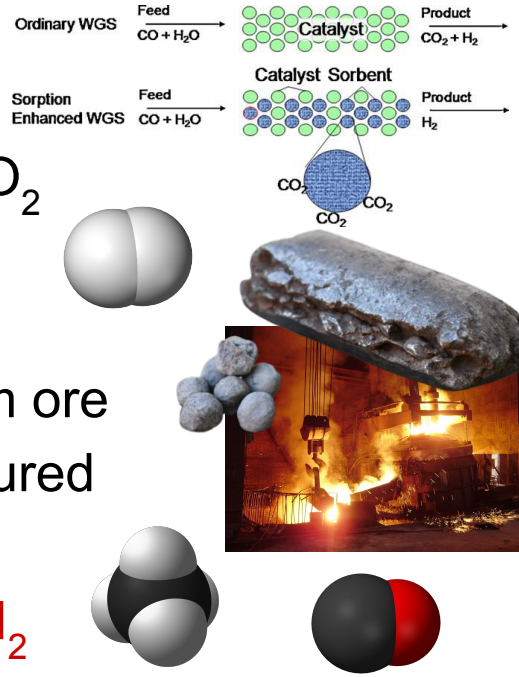
  - CSP for Fischer-Tropsch upgrading of CO + H_2 to store energy and regenerate input fuel stream



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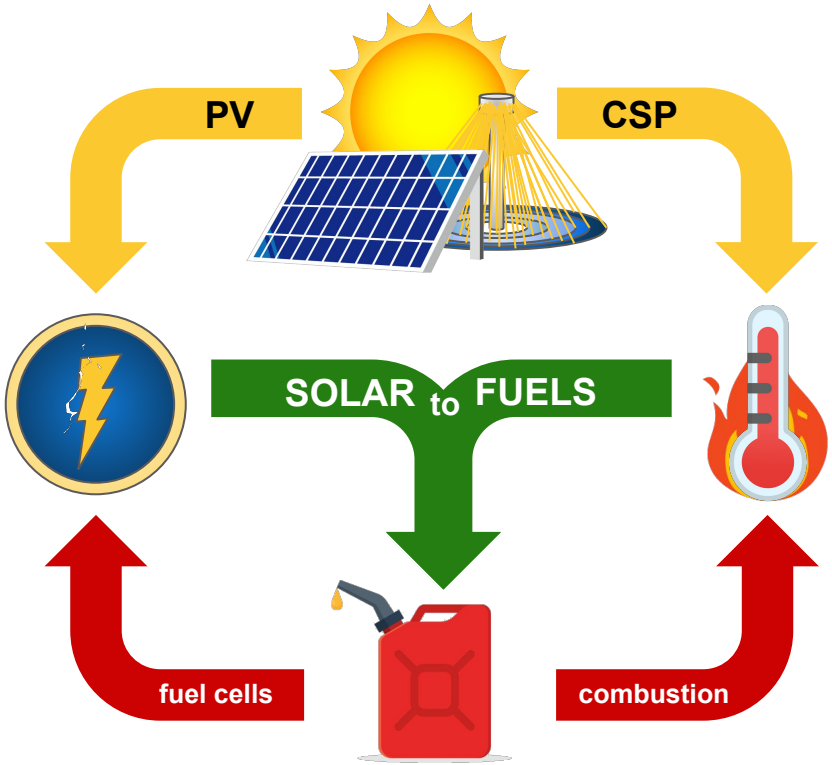
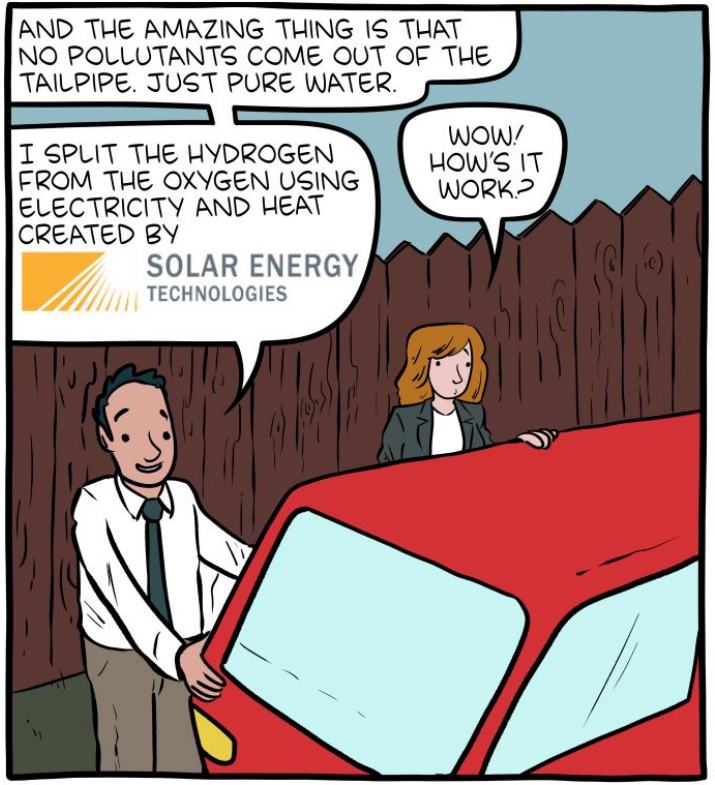
The Future


PV
CSP
SOLAR to FUELS
fuel cells
combustion


AND THE AMAZING THING IS THAT NO POLLUTANTS COME OUT OF THE TAILPIPE. JUST PURE WATER.
I SPLIT THE HYDROGEN FROM THE OXYGEN USING ELECTRICITY AND HEAT CREATED BY
SOLAR ENERGY TECHNOLOGIES
WOW! HOW'S IT WORK?