U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

SOLAR ENERGY TECHNOLOGIES OFFICE

Unlocking Solar Thermochemical Potential:

Markets, Opportunities, and Challenges

R&D Virtual Workshop Series

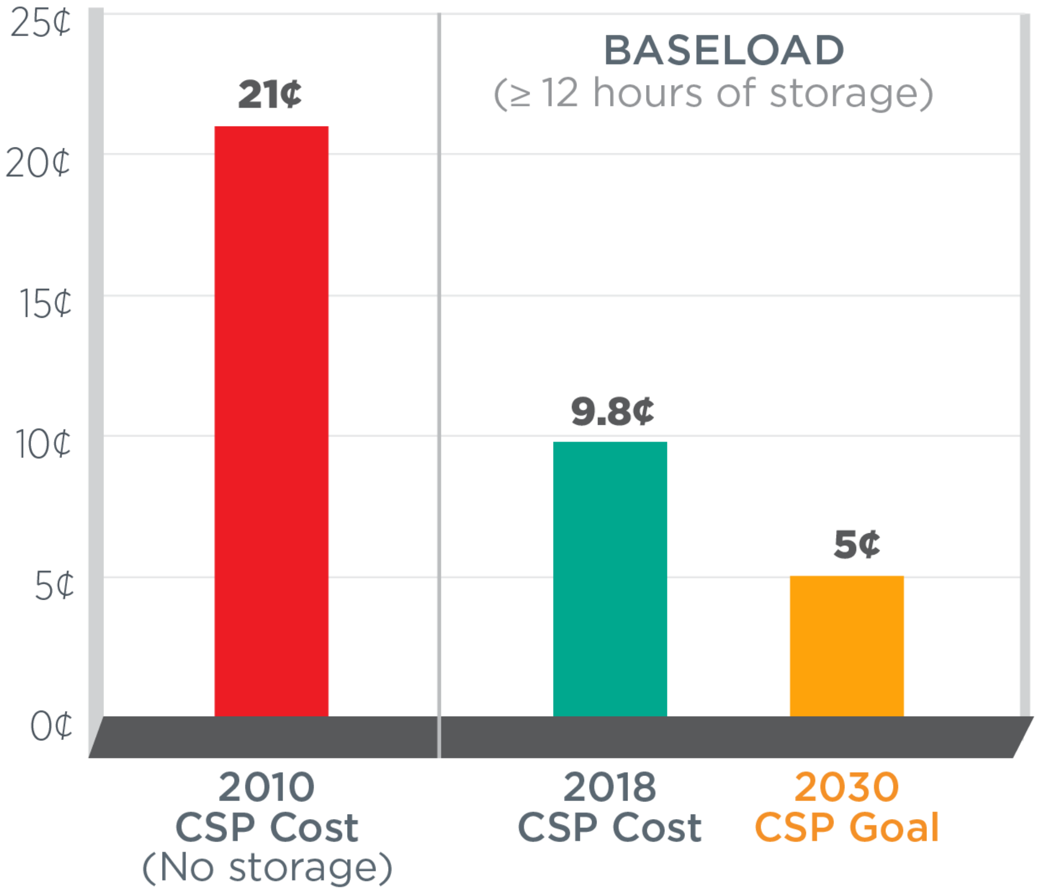
Concentrating Solar Power Program

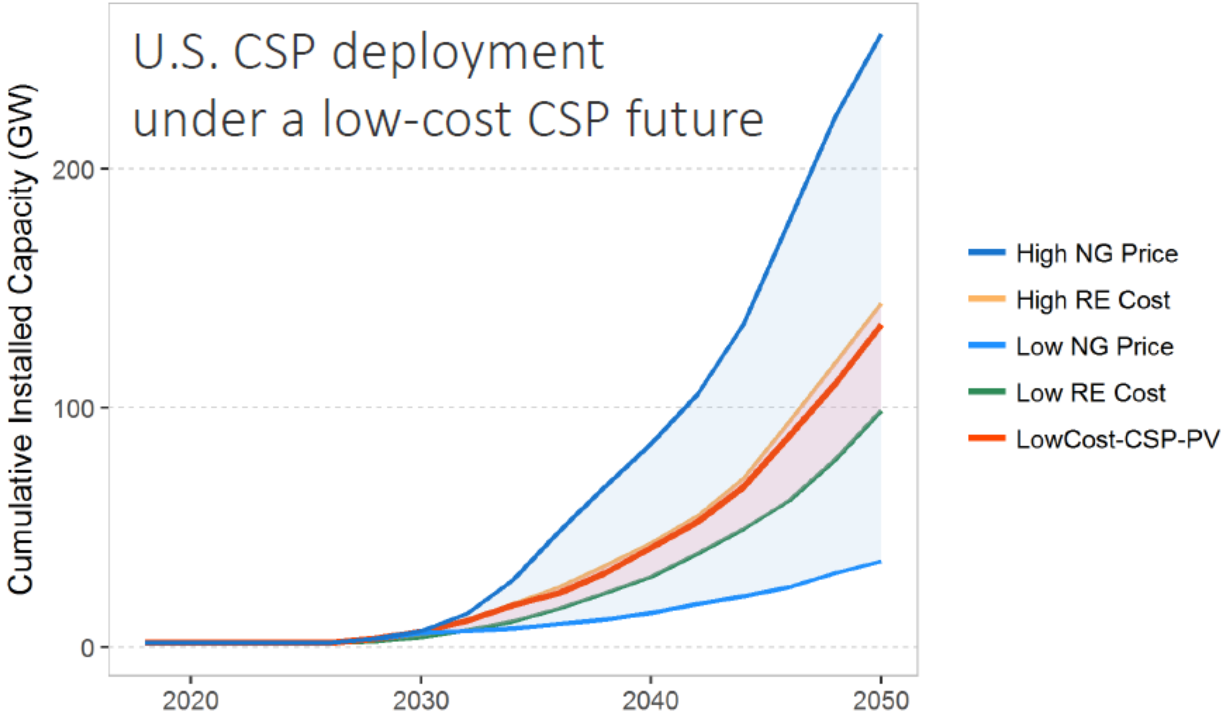
Avi Shultz, CSP Program Manager, US DOE

Levi Irwin, CSP Technology Manager, Contractor to US DOE

Levi.Irwin@ee.doe.gov

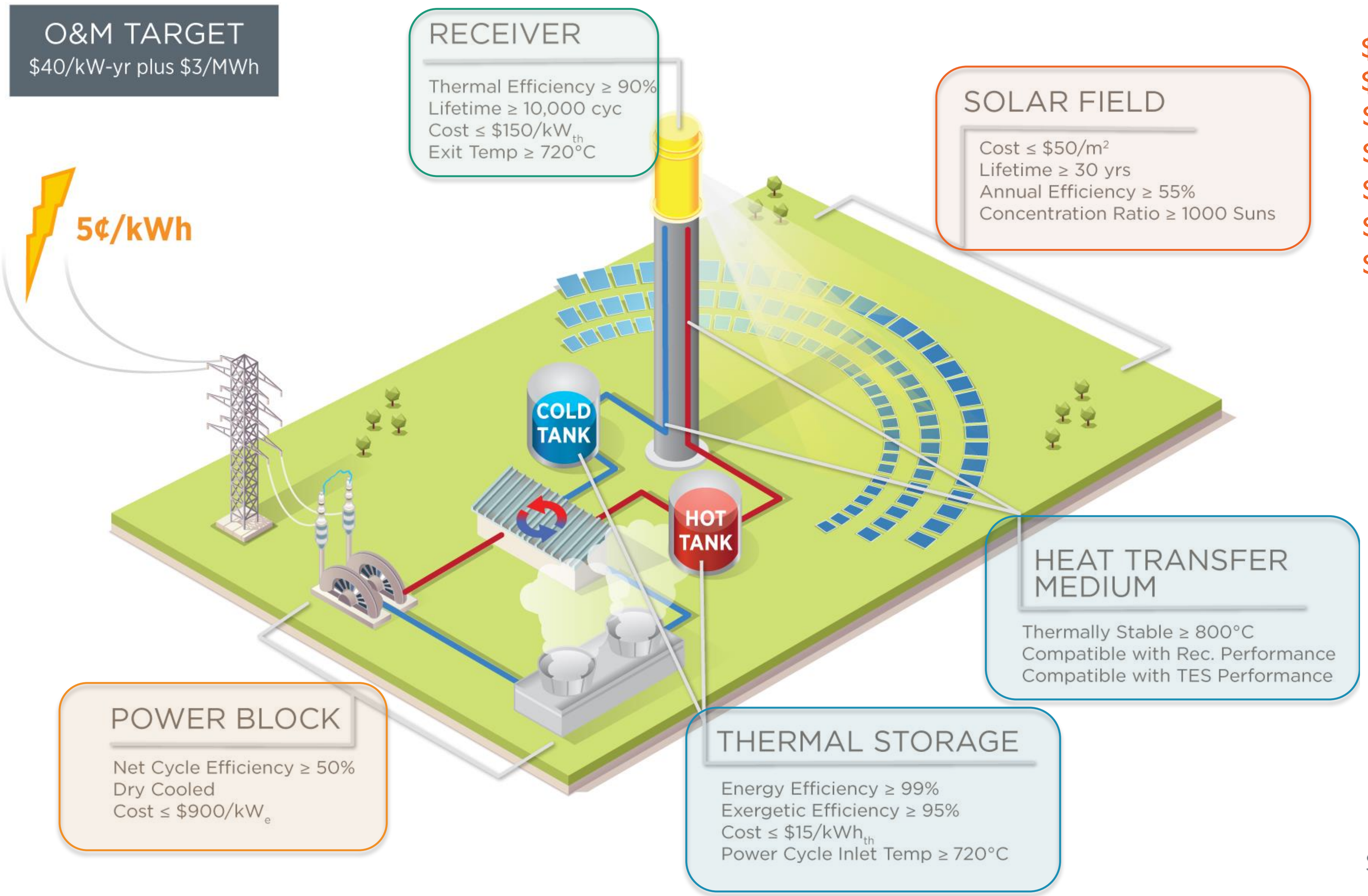
Progress and Goals: 2030 LCOE Goals





Murphy, et al. **2019**, NREL/TP-6A20-71912

CSP Technical Targets



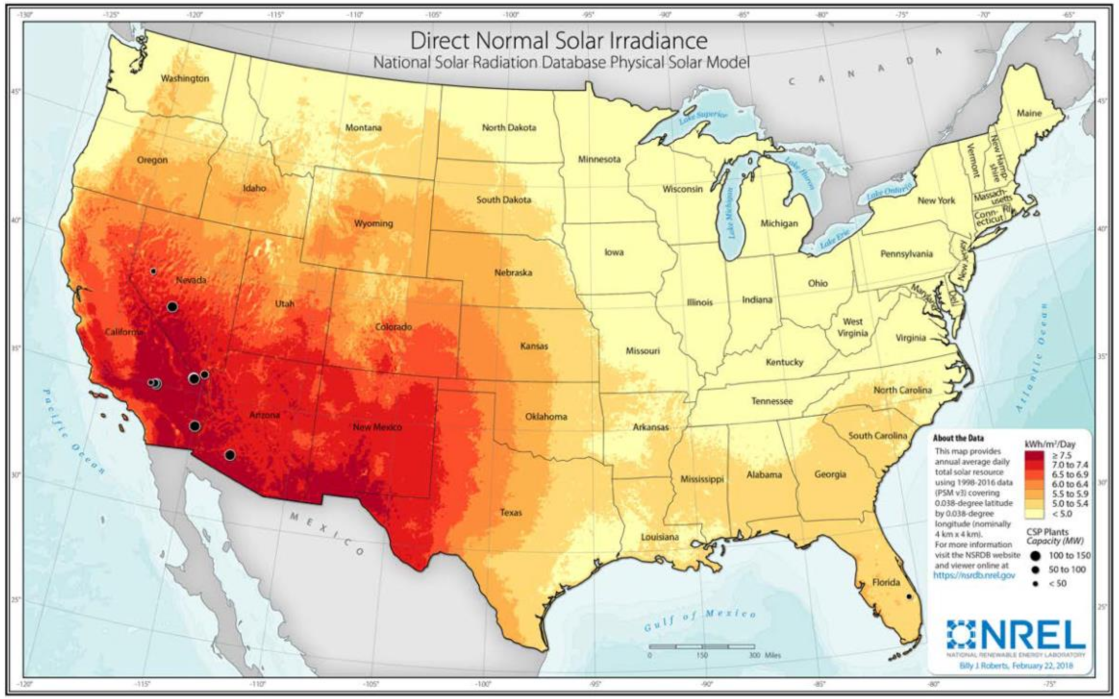
Competitive Programs

$43M	FY 2020 SETO FOA (2020)
$30M	FY 2019 SETO FOA (2019)
$22M	FY 2018 SETO FOA (2019)
$21M	Solar Desalination (2018)
$22M	FY19-21 National Lab Call (2018)
$70M	Gen3 CSP Systems (2018)
$15M	Gen3 CSP Lab Support (2018)
$9M	COLLECTS (2016)
$32M	CSP: APOLLO (2015)
$29M	CSP SuNLaMP (2015)
$1.4M	SolarMat II (2014)
$10M	CSP: ELEMENTS (2014)
$1.1M	SunShot Incubator (Recurring)
$4M	PREDICTS (2013)
$2M	SolarMat (2013)
$10M	CSP-HIBRED (2013)
$27M	National Lab R&D (2012)
$10M	SunShot MURI (2012)
$56M	CSP SunShot R&D (2012)
$0.5M	BRIDGE (2012)
$62M	CSP Baseload (2010)

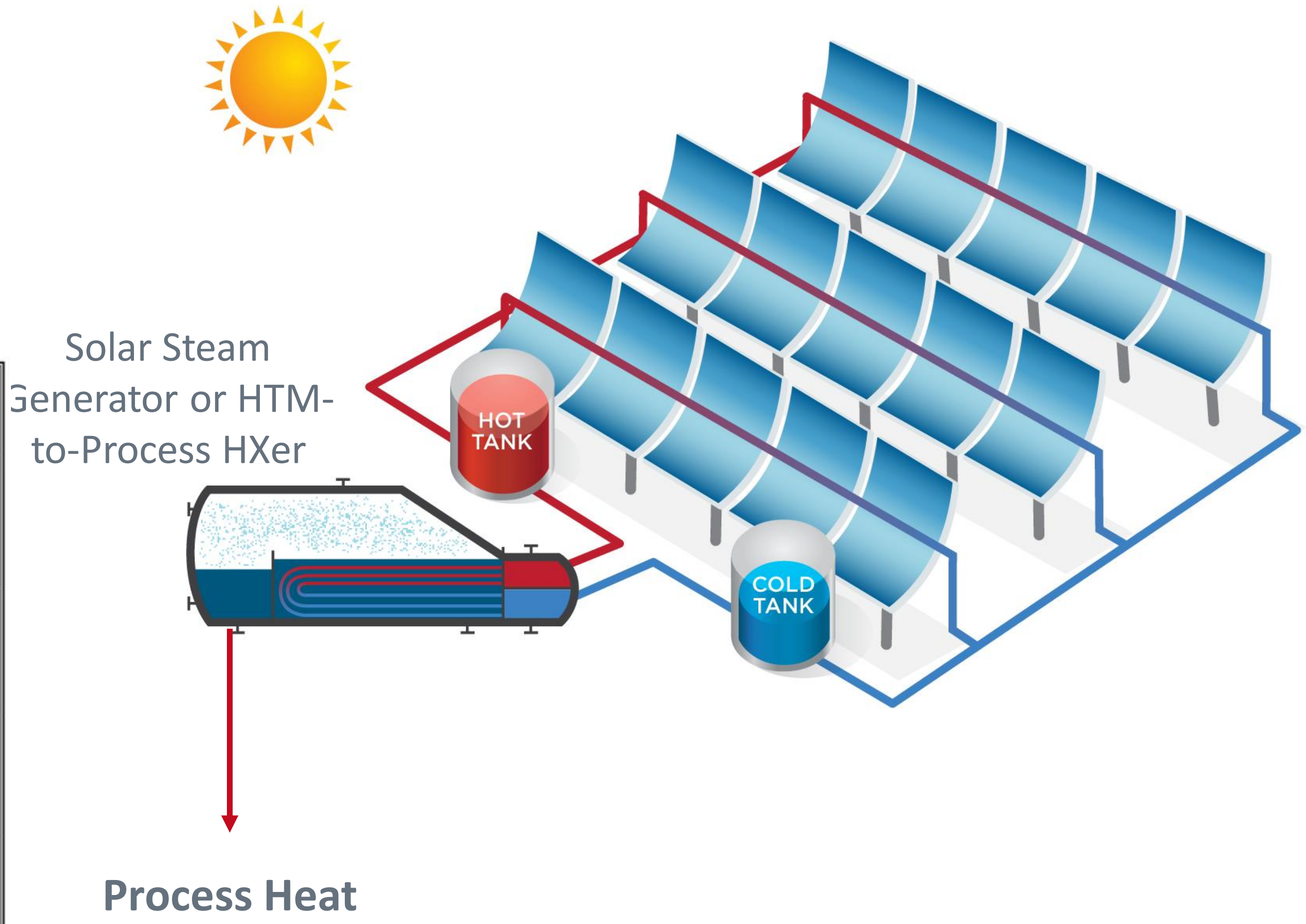
Solar Thermal Industrial Process Heat

Thermally-Driven Industrial Processes:

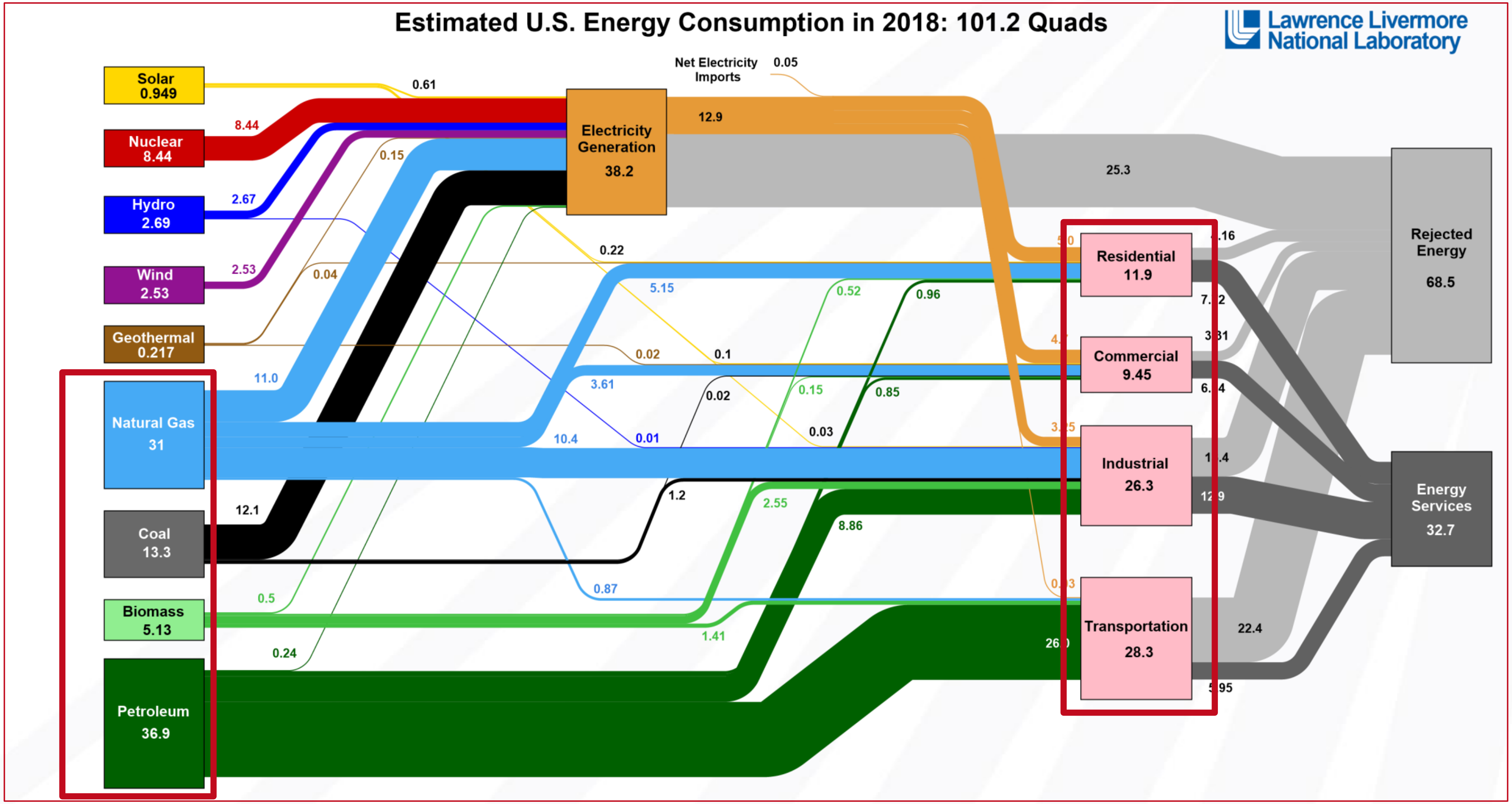
- Desalination
- Enhanced Oil Recovery
- Agriculture and Food Processing
- Fuel and Chemicals Production
- Mining and Metals Processing



SOLAR PROCESS HEAT



Solar Thermal can Integrate with the Existing Energy System



U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

SOLAR ENERGY TECHNOLOGIES OFFICE

CSP R&D Virtual Workshop Series

UPCOMING WEBINARS:

- Pumped Thermal Energy Storage Innovations
  November 17 | 1:00 p.m. to 5:00 p.m. ET
- Unlocking Solar Thermochemical Potential: Leveraging CSP Experience for Solar Thermochemistry
  November 19 | 11:00 a.m. to 2:00 p.m. ET
- Unlocking Solar Thermochemical Potential: Receivers, Reactors, and Heat Exchangers
  December 3 | 11:00 a.m. to 2:00 p.m. ET
- CSP Performance and Reliability Innovations
  December 10 | 11:00 a.m. to 2:00 p.m. ET

U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

SOLAR ENERGY TECHNOLOGIES OFFICE

Unlocking Solar Thermochemical Potential:

Markets, Opportunities, and Challenges

R&D Virtual Workshop Series

Concentrating Solar Power Program

Levi Irwin, CSP Technology Manager, Contractor to US DOE

Levi.Irwin@ee.doe.gov

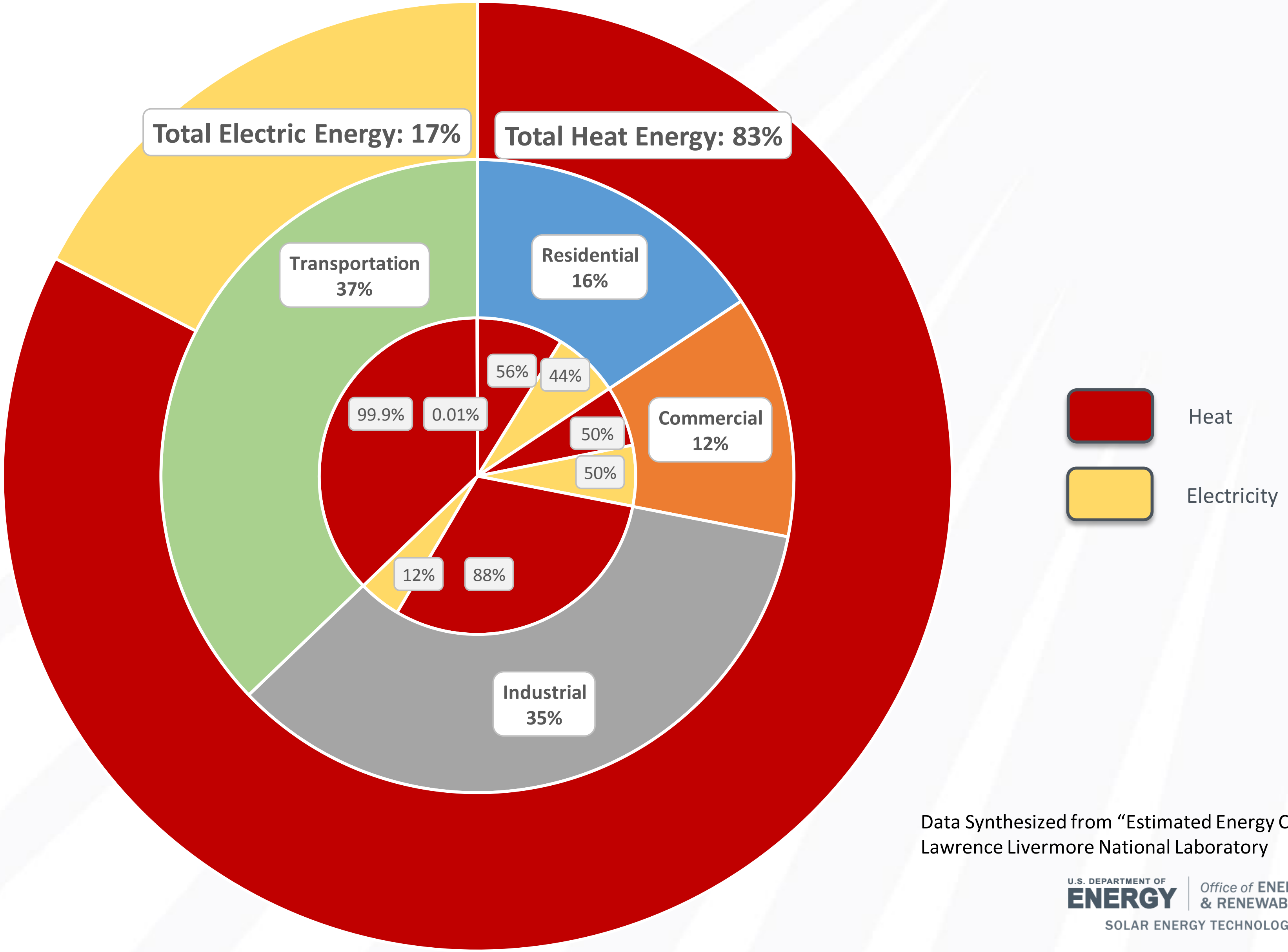
energy.gov/solar-office

Solar Thermochemical Systems – What Are They?

- Being a Concentrating Solar Thermal Facility and a Chemical Processing Facility
  - May or may not also produce power (electricity)
- The chemical may be stored and re-used on site or shipped off-site as a finished product
  - Includes the preparation of fuels, commodity chemicals
- Green field or brown field?
  - New infrastructure; new process
  - Append to existing infrastructure; (slight) mod to process

Why Concentrating Solar *Thermal* in Addition to Power

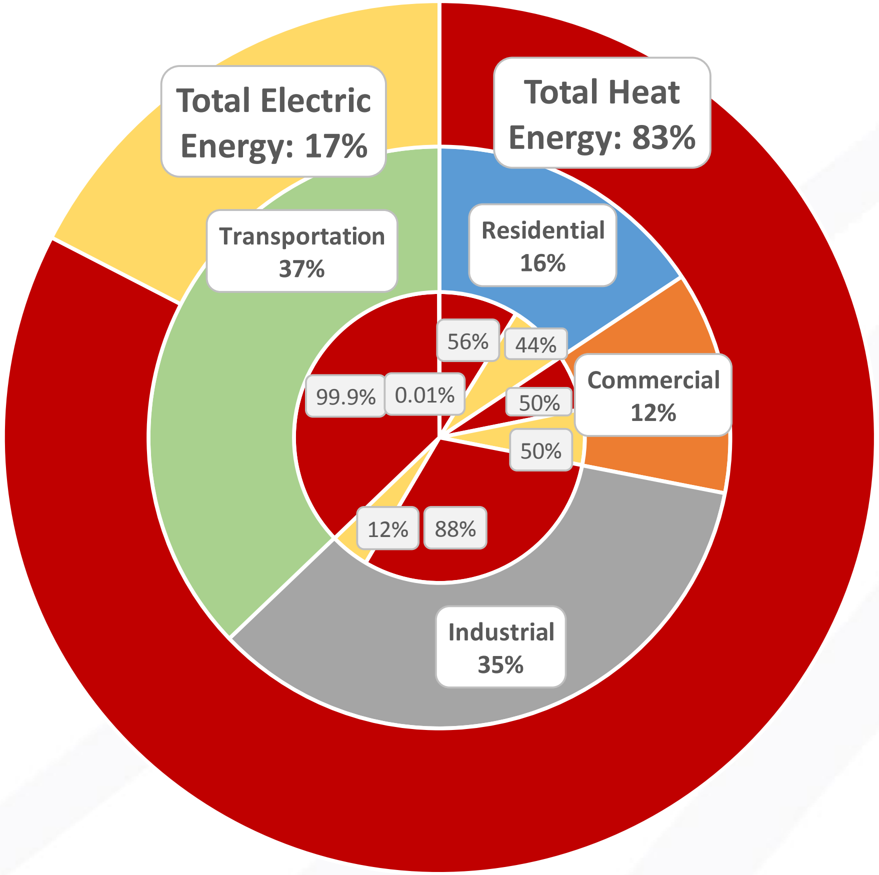
U.S. Energy use by Sector



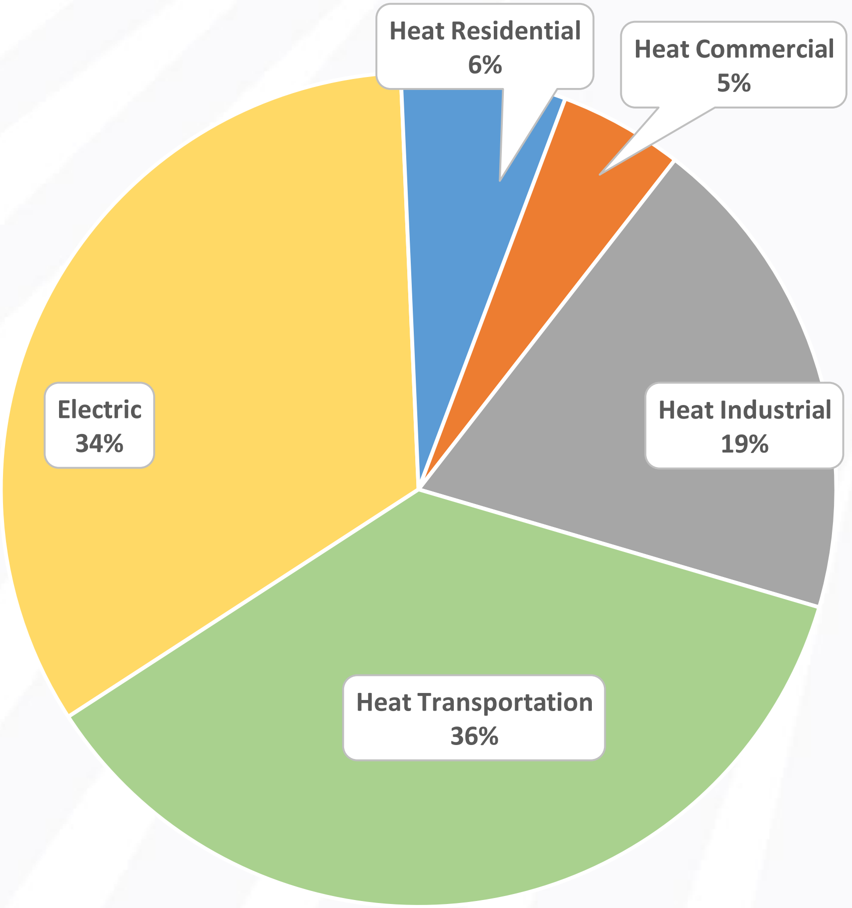
Data Synthesized from "Estimated Energy Consumption in 2019"
Lawrence Livermore National Laboratory

Why Concentrating Solar *Thermal* in Addition to Power
U.S. Carbon Dioxide Emissions by Sector

Energy Use

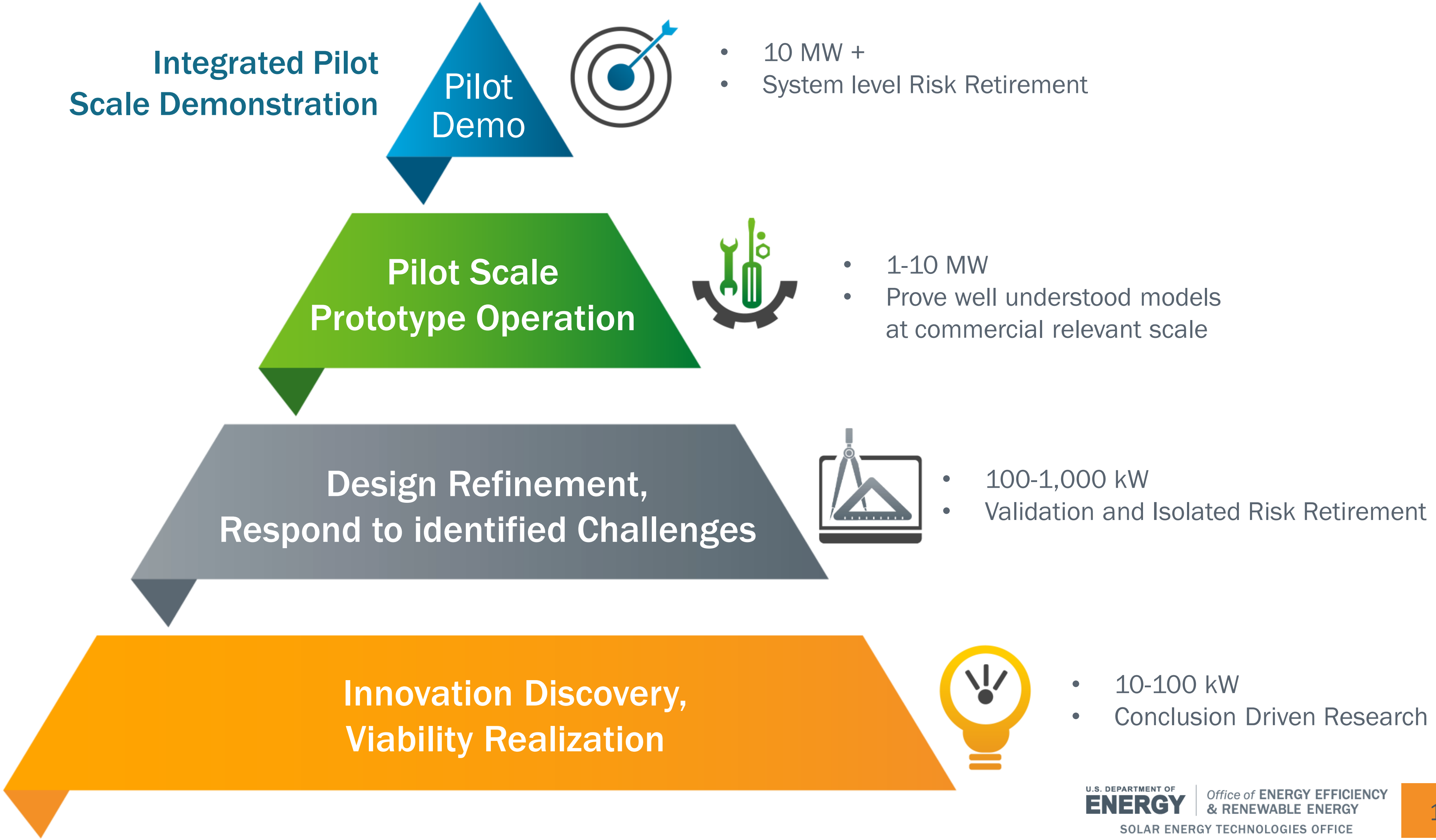


CO_2 Emissions



Data Synthesized from "US Carbon Dioxide Emissions in 2018"
Lawrence Livermore National Laboratory

Thinking through Risk within Tiers of Technology Maturity



Workshop Goals

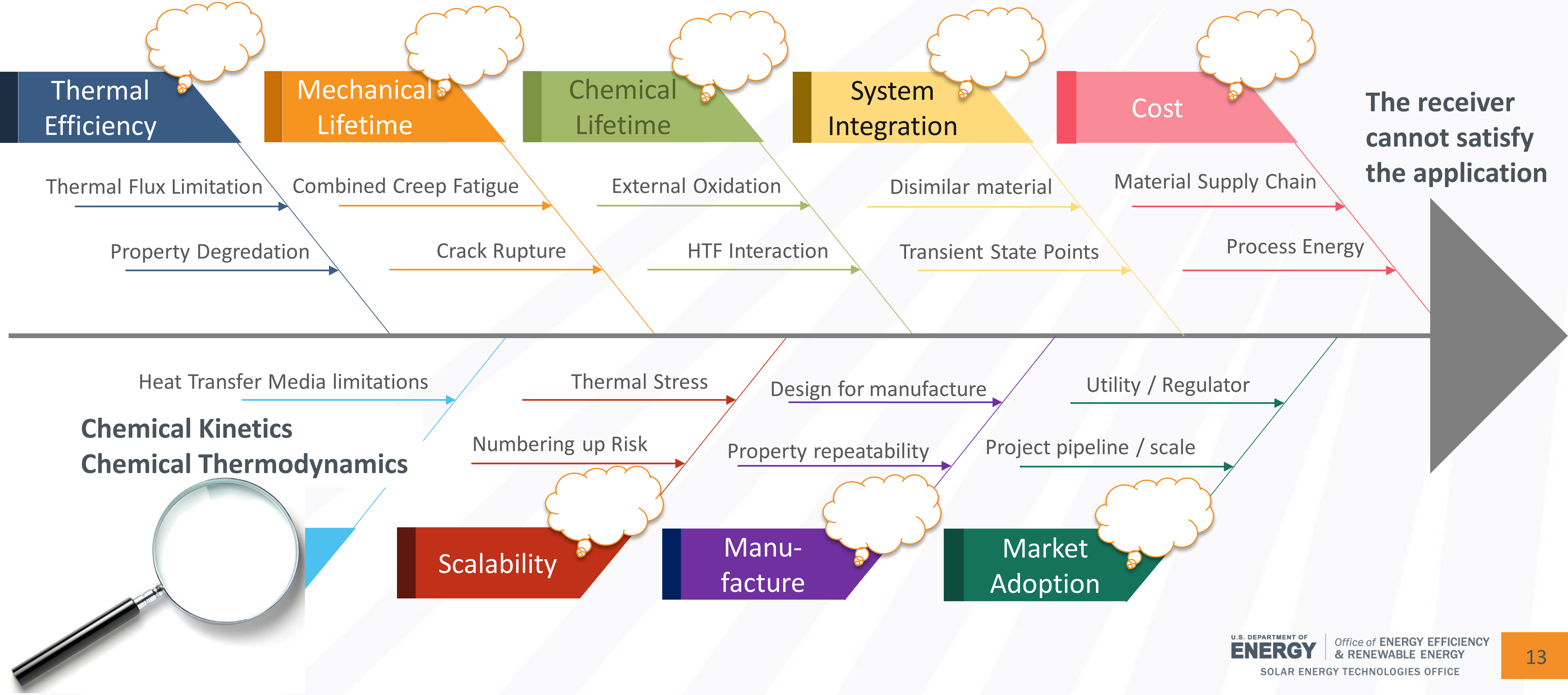
For both Panel 1 and Panel 2:
How can systems-level analysis direct innovation from lab-scale research to on-sun demonstration to commercial deployments?

- What are key risks that are often overlooked early in the development process?
- How should testing campaigns be designed to manage those risks?
- What are overlooked technical metrics/objectives that should be considered at both early and late stages?
- How do you approach balancing constraints between the solar component and the remainder of the system?

How should research outcomes be packaged so as to draw attention from industry and other private sponsors?

Thermochemical Concerns Compound with Innovative Receivers

Ishikawa diagram approach — Be thinking about how thermochemical nests into all these…



Agenda

Time	Session
11:00AM–11:20AM	**Introduction and Workshop Overview** Avi Shultz, *DOE Program Manager, Concentrating Solar Power* Levi Irwin, *Technology Manager, Concentrating Solar Power*
11:20AM–12:30PM	**Panel – Systems in the Solar Thermochemical Context** Joseph Cresko, *DOE Advanced Manufacturing Office* Ellen Stechel, *Arizona State University* Davide Zampini, *Cemex* Peter Pfromm, *Washington State University*
12:30PM–1:30PM	**Panel – A Systems Look at Solar Thermochemical Hydrogen** Ron Kent, *SoCal Gas* Vikas Tuteja, *Heliogen* Philipp Furler, *Synhelion*
1:30 PM	**Closing Remarks** Avi Shultz, *Department of Energy*

Systems in the Solar Thermochemical Context

~Our Panelists~

Joseph Cresko

DOE Advanced Manufacturing Office

Ellen Stechel

Arizona State University

Davide Zampini

Cemex

Peter Pfromm

Washington State University

Workshop Goals

For both Panel 1 and Panel 2:

How can systems-level analysis direct innovation from lab-scale research to on-sun demonstration to commercial deployments?

- What are key risks that are often overlooked early in the development process?
- How should testing campaigns be designed to manage those risks?
- What are overlooked technical metrics/objectives that should be considered at both early and late stages?
- How do you approach balancing constraints between the solar component and the remainder of the system?

How should research outcomes be packaged so as to draw attention from industry and other private sponsors?

Agenda

Time	Session
11:00AM–11:20AM	**Introduction and Workshop Overview** Avi Shultz, *DOE Program Manager, Concentrating Solar Power* Levi Irwin, *Technology Manager, Concentrating Solar Power*
11:20AM–12:30PM	**Panel – Systems in the Solar Thermochemical Context** Joseph Cresko, *DOE Advanced Manufacturing Office* Ellen Stechel, *Arizona State University* Davide Zampini, *Cemex* Peter Pfromm, *Washington State University*
12:30PM–1:30PM	**Panel – A Systems Look at Solar Thermochemical Hydrogen** Ron Kent, *SoCal Gas* Vikas Tuteja, *Heliogen* Philipp Furler, *Synhelion*
1:30 PM	**Closing Remarks** Avi Shultz, *Department of Energy*

A Systems Look at Solar Thermochemical Hydrogen

~Our Panelists~

Ron Kent

SoCal Gas

Vikas Tuteja

Heliogen

Philipp Furler

Synhelion

Workshop Goals

For both Panel 1 and Panel 2:
How can systems-level analysis direct innovation from lab-scale research to on-sun demonstration to commercial deployments?

- What are key risks that are often overlooked early in the development process?
- How should testing campaigns be designed to manage those risks?
- What are overlooked technical metrics/objectives that should be considered at both early and late stages?
- How do you approach balancing constraints between the solar component and the remainder of the system?

How should research outcomes be packaged so as to draw attention from industry and other private sponsors?

SOLAR ENERGY TECHNOLOGIES OFFICE

CSP R&D Virtual Workshop Series

UPCOMING WEBINARS:

- Pumped Thermal Energy Storage Innovations
  November 17 | 1:00 p.m. to 5:00 p.m. ET
- Unlocking Solar Thermochemical Potential: Leveraging CSP Experience for Solar Thermochemistry
  November 19 | 11:00 a.m. to 2:00 p.m. ET
- Unlocking Solar Thermochemical Potential: Receivers, Reactors, and Heat Exchangers
  December 3 | 11:00 a.m. to 2:00 p.m. ET
- CSP Performance and Reliability Innovations
  December 10 | 11:00 a.m. to 2:00 p.m. ET

Industrial Thermal Process Intensification

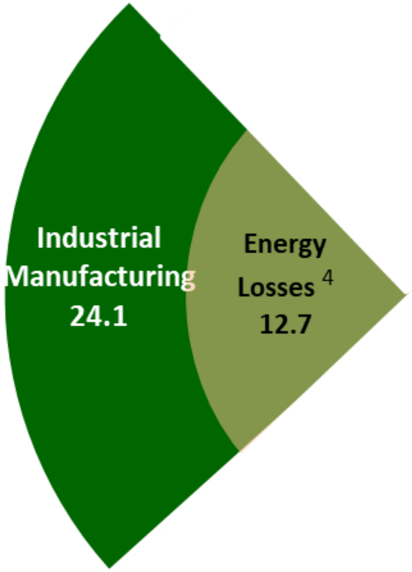
Joe Cresko – Chief Engineer, AMO
joe.cresko@ee.doe.gov

November 12th 2020

Opportunity Space for Manufacturing

- Improve the energy and carbon productivity of U.S. manufacturing.
- Reduce life cycle energy and resource impacts of manufactured goods.

Manufacturing Goods



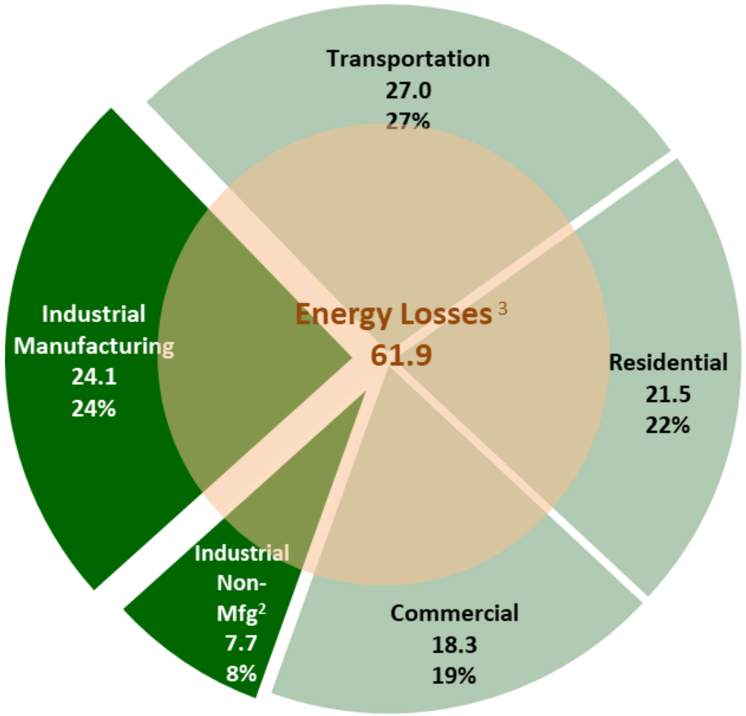
Data for 2014

More efficient manufacturing reduces energy losses

More efficient manufacturing enables technologies that improve energy use throughout the economy:

- Transportation
- Buildings
- Energy Production and Delivery

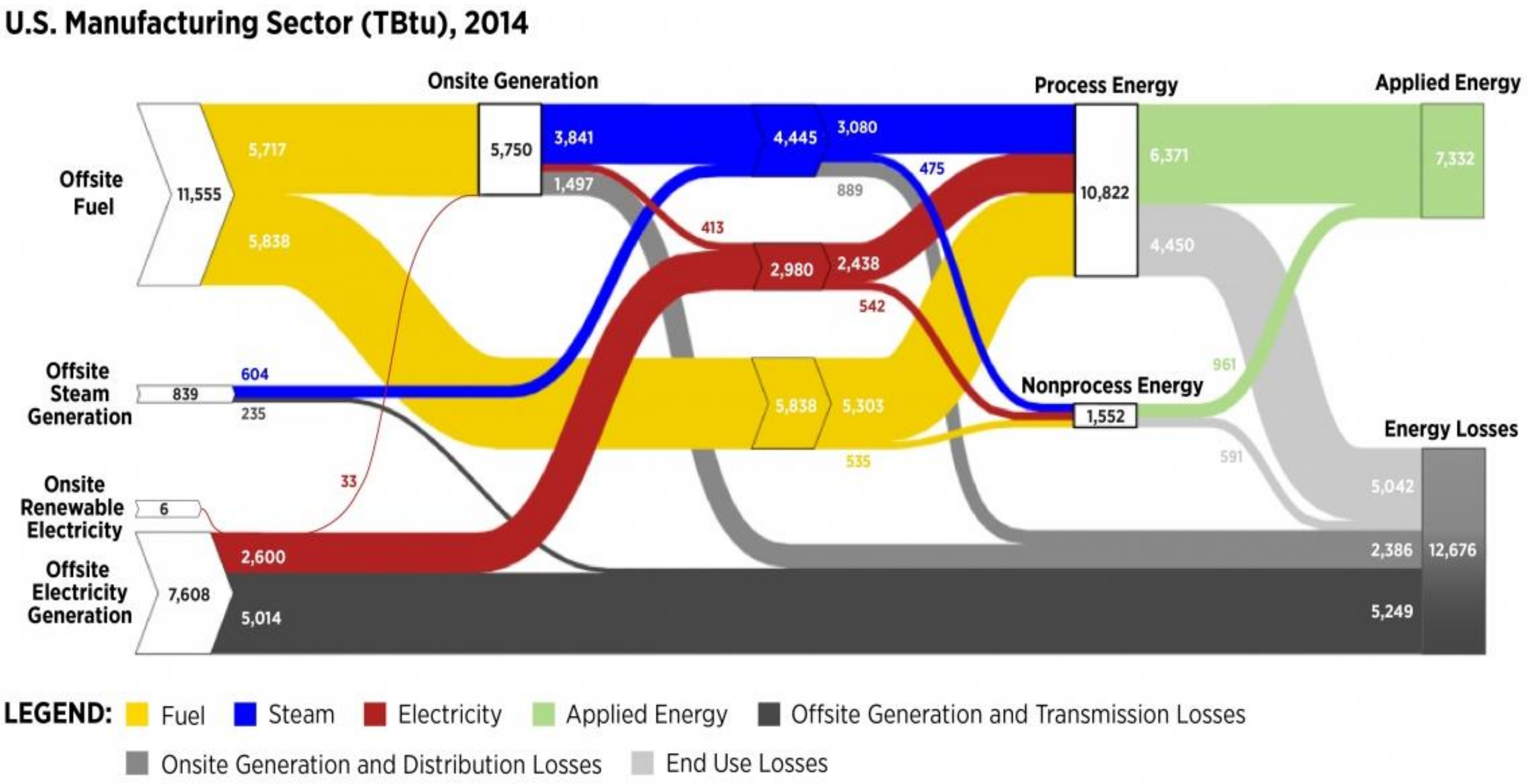
Use of Manufactured Goods



U.S. Energy Economy by Sector
98.5 quadrillion Btu, 2014 [1]

[1] Energy consumption by sector from EIA Monthly Energy Review, 2018
[2] Industrial non-manufacturing includes agriculture, mining, and construction
[3] US economy energy losses determined from LLNL Energy Flow Chart 2014 (Rejected Energy), adjusted for manufacturing losses
[4] Manufacturing energy losses determined from DOE AMO Footprint Diagrams (2014 data)

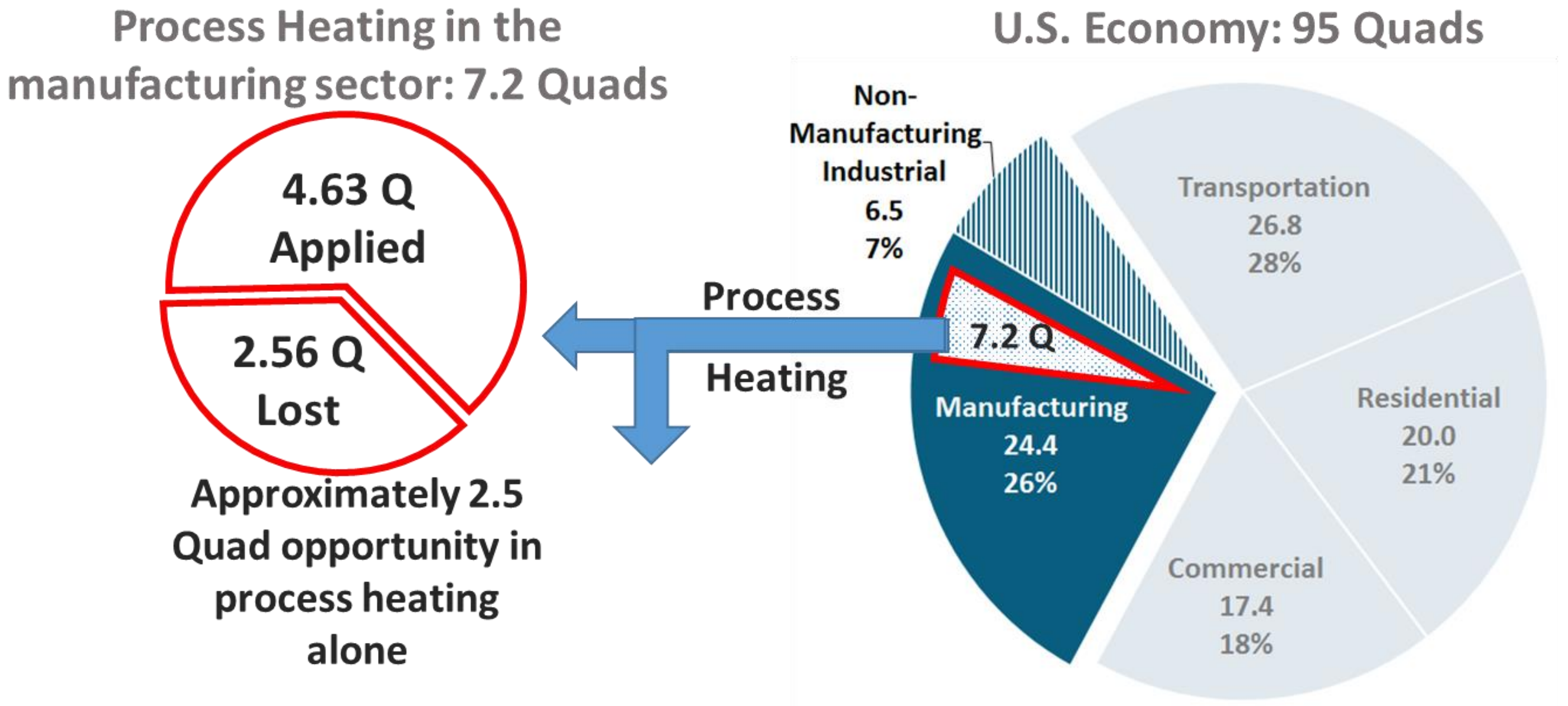
Sankey Diagram of Energy Flows in the U.S Manufacturing Sector



https://www.energy.gov/eere/amo/energy-analysis-data-and-reports

Thermal Opportunity

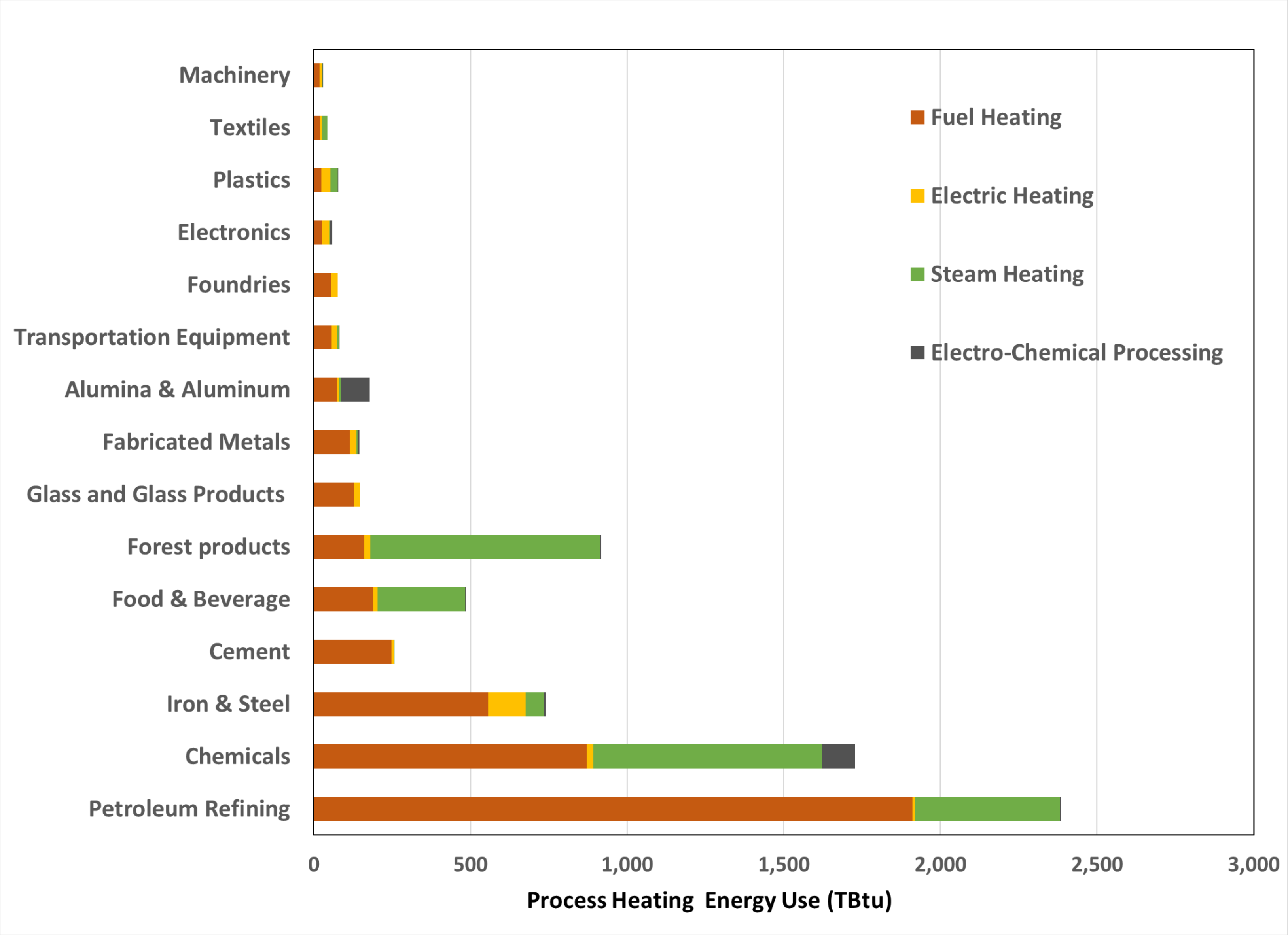
Process Heating Energy Use/Loss in the U.S. Economy



Source: EIA Monthly Energy Review, Aug 2014; AEO 2014

- **7 Quads opportunity space**. Process heating accounts for a sizable fraction of total U.S. energy use, and more direct energy use than any other energy consuming processes in manufacturing. Currently process heating is 95% fossil fuel based. .
- **95% fossil fuel based**. Traditional industrial (thermal) processes can be inefficient, difficult to control and result in materials and products with compromised quality and performance.
- **> 1 Quad potential**. Assuming half of the energy lost in current process heating operations can be avoided, this represents a > 1% reduction in the total energy used in the U.S. economy.

Energy Used for Thermal Processing



In the U.S., the total energy consumed for thermal processing in these 8 industries is roughly 95% the total energy consumed for thermal processing in all U.S. industries

Source: EIA MECS 2014

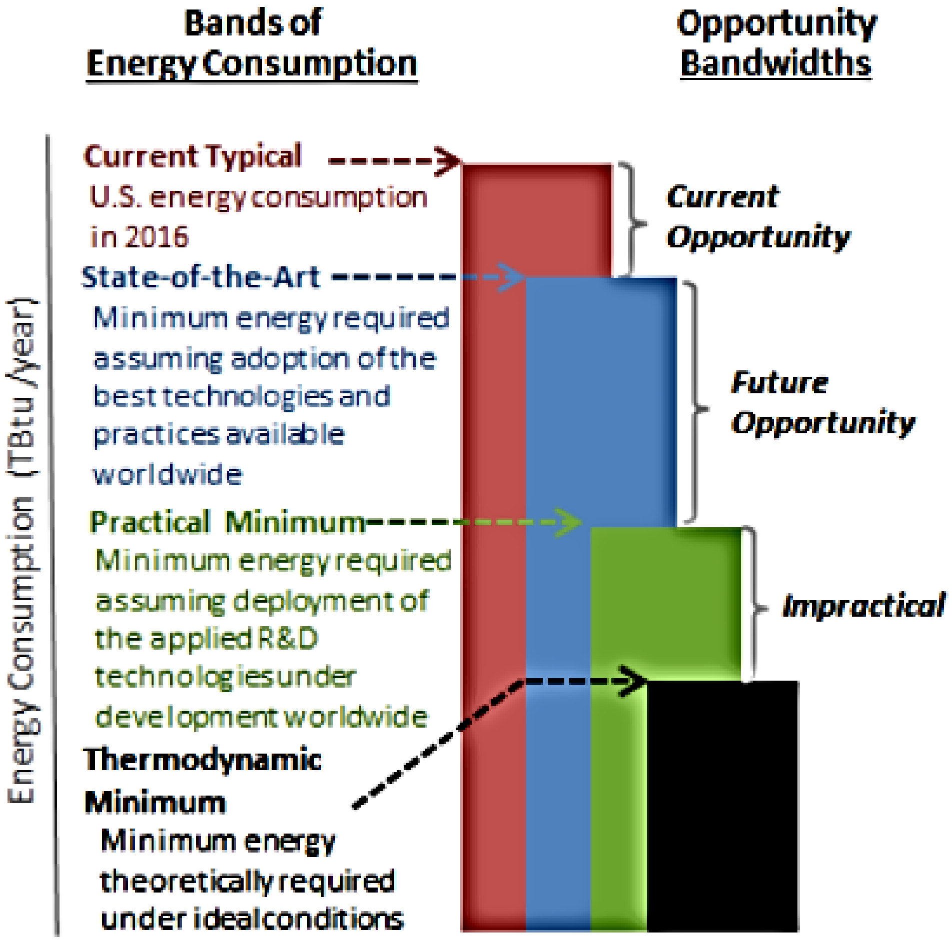
Type of Thermal Processes Used for Eight Large Energy Consuming Industries

Temperature Range	Color
Low Temperature (<800°F)	
Medium Temperature (800 to 1400°F)	
High Temperature (>1400°F)	

Thermal Process Step	Iron & Steel	Petroleum Refining	Chemical Industry	Glass	Aluminum	Pulp & Paper	Food Processing	Cement
Calcining	High		High		High	High		High
Curing and forming			Low					
Drying			Medium			Low	Low	
Fluid heating		Medium	Medium			Low	Low	
Heat treating (metal & nonmetal)	Medium			Medium	Medium			
Metal and non-metal reheating	High				Medium			
Metal and non-metal melting	High			High	Medium			
Other heating - processing			Medium					
Reactive thermal processing	High	Medium	Medium					
Smelting, agglomeration, etc.	High		Medium					
Steam generation	Medium	Medium	Medium		Medium	Medium	Medium	

Manufacturing Energy Bandwidth Studies

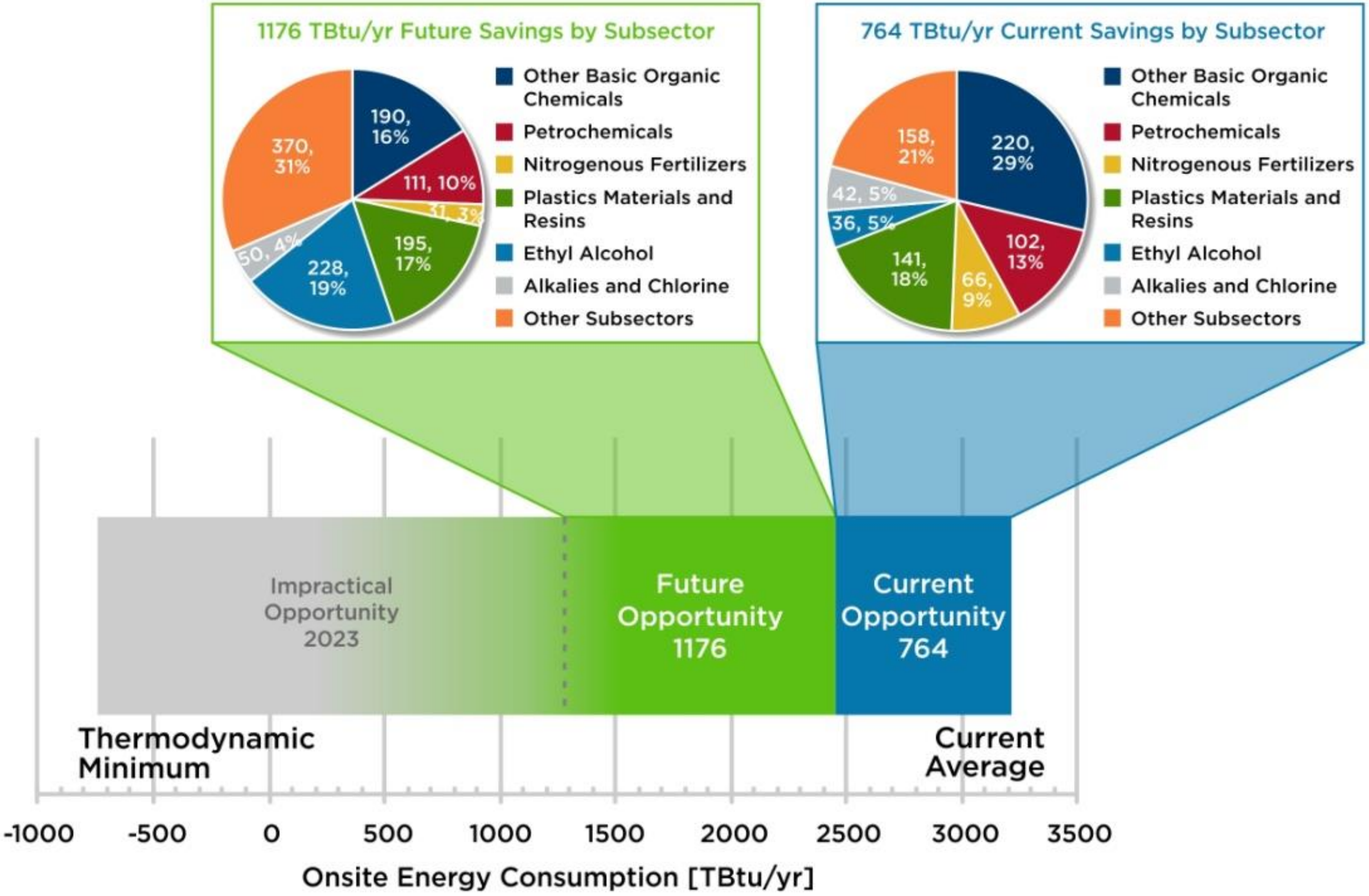
Energy Consumption Bands and Opportunity Bandwidths Estimated in the Bandwidth Study



- Energy bandwidth studies of U.S. manufacturing sectors serve as general data references to help understand the range (or *bandwidth*) of potential energy savings opportunities
- The consistent methodology used in the bandwidth studies provides a framework to evaluate and compare energy savings potentials within and across manufacturing sectors at the macro-scale

Source: https://www.energy.gov/eere/amo/energy-analysis-data-and-reports

Bandwidth Study Example – Chemicals



2015 Bandwidth Study: Chemicals

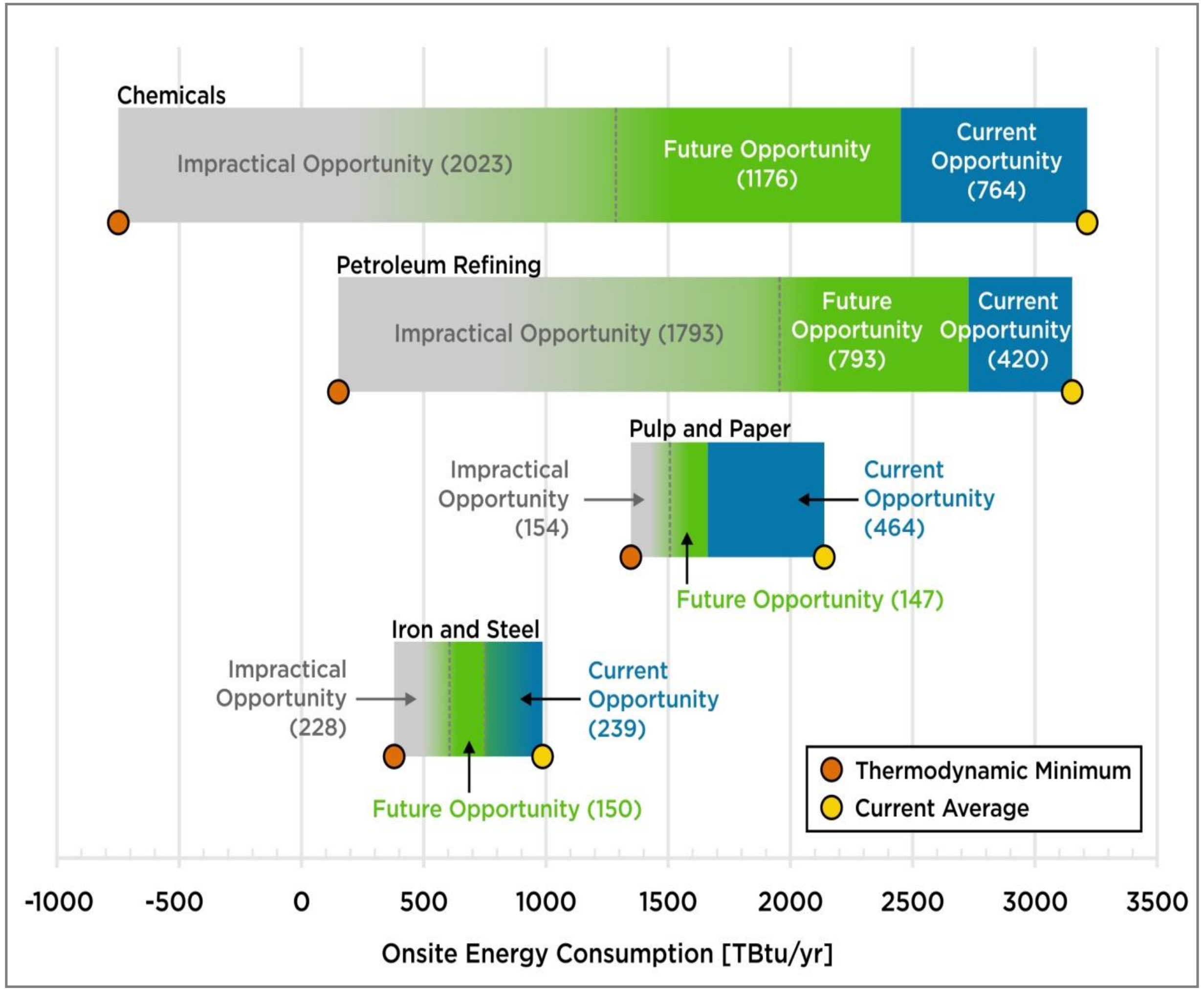
Energy Intensity

<u>Energy Intensity</u> e.g.:
Process efficiency
Process integration
Waste heat recovery

<u>Carbon Intensity</u>, e.g.:
Process efficiency
Feedstock substitution
Biomass-based fuels
Renewables

<u>Use Intensity</u> e.g.:
Circular economy Design for Re-X (recycling, reuse and remanufacturing)
Material efficiency and substitution

Technical Energy Savings Opportunities:

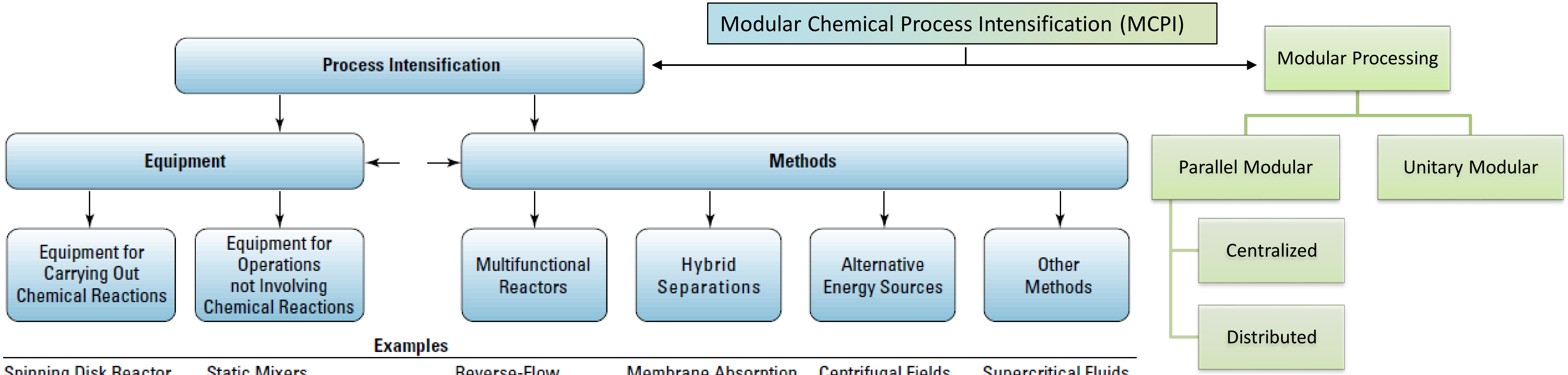


Source: DOE/AMO, Energy Bandwidth Studies (2015)
Note: 1 quad = 1000 TBtu

https://www.energy.gov/eere/amo/energy-analysis-data-and-reports

MCPI Taxonomy

RAPID™ Transforming Process Industries



Examples

Equipment for Carrying Out Chemical Reactions	Equipment for Operations not Involving Chemical Reactions	Multifunctional Reactors	Hybrid Separations	Alternative Energy Sources	Other Methods
Spinning Disk Reactor	Static Mixers	Reverse-Flow Reactors	Membrane Absorption	Centrifugal Fields	Supercritical Fluids
Static Mixer Reactor (SMR)	Compact Heat Exchangers	Reactive Distillation	Membrane Distillation	Ultrasound	Dynamic (Periodic) Reactor Operation
Static Mixing Catalysts (KATAPAKs)	Microchannel Heat Exchangers	Reactive Extraction	Adsorptive Distillation	Solar Energy	
Monolithic Reactors	Rotor/Stator Mixers	Reactive Crystallization		Microwaves	
Microreactors	Rotating Packed Beds	Chromatographic Reactors		Electric Fields	
Heat Exchange (HEX) Reactors	Centrifugal Adsorber	Periodic Separating Reactors		Plasma Technology	
Supersonic Gas/Liquid Reactor		Membrane Reactors			
Jet-Impingement Reactor		Reactive Extrusion			
Rotating Packed-Bed Reactor		Reactive Comminution			
		Fuel Cells			

Examples

Gas compression	Gas-to-Liquids
Chloralkali	Distillation

Gaps / Opportunities

- Understanding risks, cost, RAM
- Module Standardization
- Flexibility of assets
- Sensors, controls, automation

Adapted from Stankiewicz and Moulijn, *Chemical Engineering Progress*, ©2000 American Institute of Chemical Engineers.

Four Pillars of Thermal PI – Examples from RAPID's Portfolio

RAPID™ Transforming Process Industries




Low-Thermal Budget Transformative Technologies	Alternative Thermal Processing	Transformative Supplemental Technologies	Waste Heat Management Technologies
Technologies that may use alternate energy sources while offering disruptive changes in the current production methods. - Electrolysis and Electrodialysis -UV applications for disinfection -Ultrasound/RF processing for drying -Hydrogen based production of ammonia, methanol, etc.	Technologies that use alternate source of energy in manufacturing processes while maintaining the current production methods. - Induction and resistance furnaces - Microwave and RF heating pre-heaters - Hybrid fuel systems - Solar thermal systems	Emerging energy-efficiency and supplemental technologies that reduce thermal demand - Smart IOT devices for system optimization - Smart manufacturing (Digital twin, AI and Predictive Process Controls) - Flexible, modular manufacturing and operations design - Advanced materials for thermal systems	Emerging waste heat reduction, recycle, and recovery options -High temperature heat pumps -Thermal energy storage -Recuperators, regenerators and economizers for non - traditional applications -Thermoelectric devices , heat pipes, etc. -Waste heat to power, District heating, desalination, green-house heating, etc.

RAPID™ Transforming Process Industries

Alternative Thermal Processing

Manufacturing Supply Chain for Modular Solar-Thermochemical Conversion

Additive manufacturing and modular designs for distributed, solar-driven reforming of natural gas to hydrogen

Pacific Northwest NATIONAL LABORATORY

Oregon State University

STARS Technology Corporation

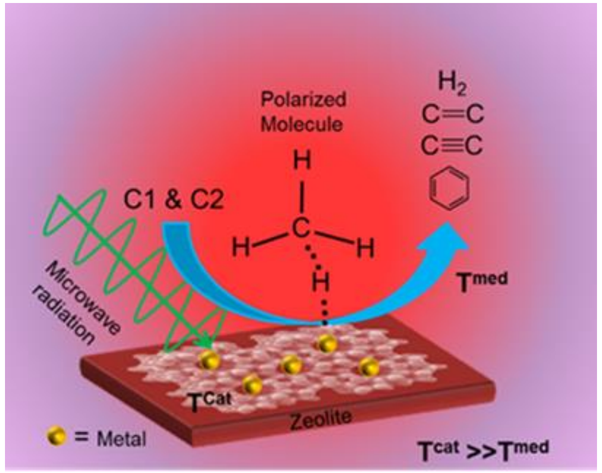
SoCalGas

Alternative Energetics for Hydrocarbon Upgrading

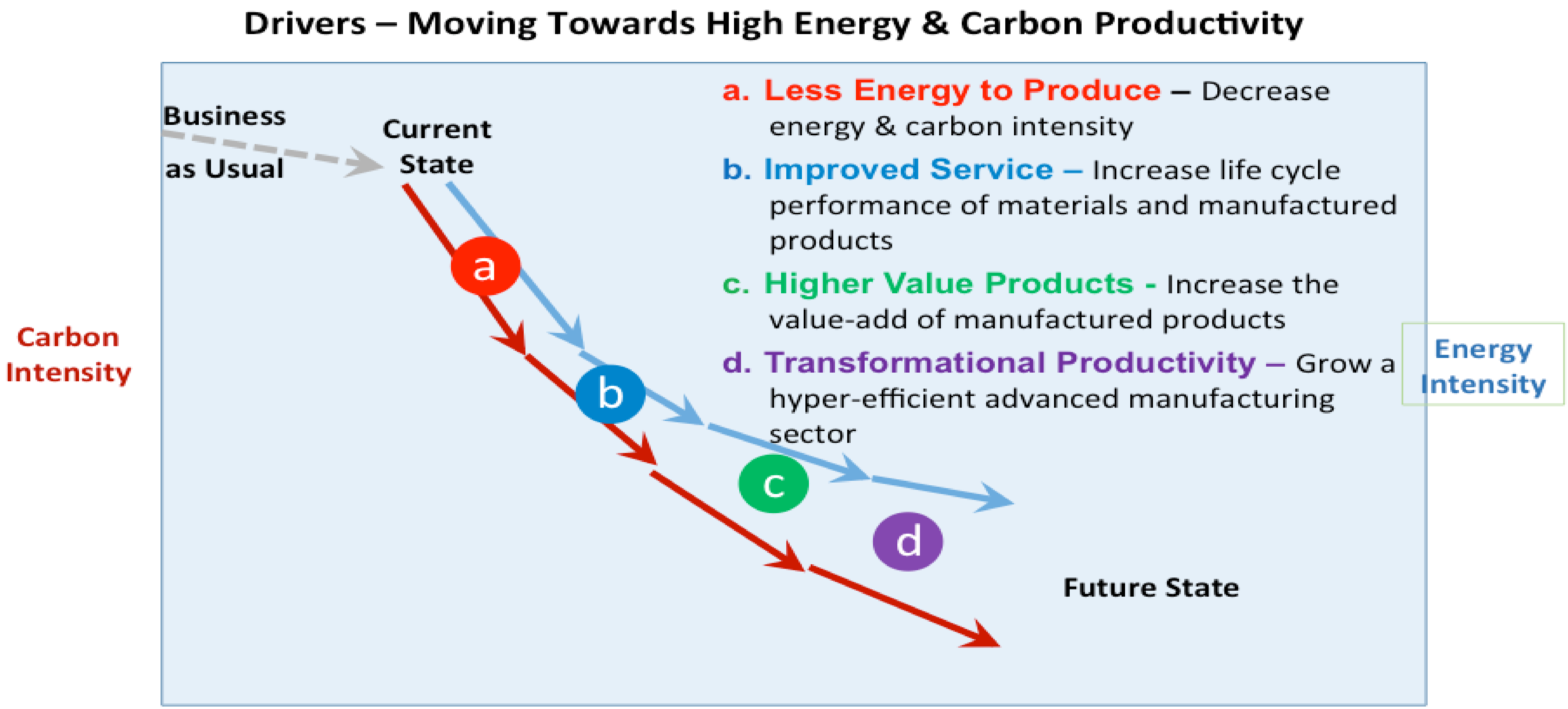
A viable reactor and catalysts for direct conversion of lower alkanes to aromatics using selective microwave heating

WestVirginiaUniversity

NATIONAL ENERGY TECHNOLOGY LABORATORY



What is Potential to Decouple Thermal Operations in Mfg.?



Thanks!

joe.cresko@ee.doe.gov

Thermal Process Intensification:

Transforming the Way Industry Uses Thermal Process Energy

November 5 - December 9, 2020

https://www.orau.gov/2020thermal

	High Temperature Metals	High Temperature Non - Metallic Minerals	Low/Medium Temperature Processing	Hydrocarbon Processing Industry
Session 0 - Plenary Session (November 5th at Noon – 3:00 pm ET)				
Pillar 1 & 2 – Transformative Low Thermal Budget and Alternative Thermal Processing	Session1 November 9 (Noon to 2:00 pm ET)	Session 2 November 12 (Noon to 2:00 pm ET)	Session 3 November 16 (Noon to 2:00 pm ET)	Session 4 November 20 (Noon to 2:00 pm ET)
Pillar 3 – Transformative Supplemental Technologies	Session 5 - Dec 2nd (Noon to 3:00 pm ET)			
Pillar 4 – Waste Heat Management Technologies	Session 6 - Dec 9th (Noon to 3:00 pm ET)			

LightWorks®

Unlocking Solar Thermochemical Potential Workshop

Panelist Ellen B. Stechel

ASU LightWorks®, Arizona State University, Tempe AZ, USA

COLLABORATORS

Arizona State University: Shuguang Deng, Ivan Ermanoski, James E. Miller, Ryan Milcarek, Chris Muhich
Georgia Institute of Technology: Peter Loutzenhiser
National Renewable Energy Laboratory: David Ginley, Karen Heinselman, Bob Bell, Phil Parilla, Dan Plattenberger, Sarah Shulda
Oregon State University: Brian Fronk
Princeton University: Emily Carter (now UCLA), Sai Gautam (now IISc), Rob Wexler
Sandia National Laboratories: Kevin Albrecht, Andrea Ambrosini, Evan Bush, Eric Coker, Matt Kury, Tony McDaniel
Siemens Corporation: Ioannis Akrotirianakis, Arindam Dasgupta, Ayse Parlak
Southwest Research Institute: Stefan Cich, Josh Neveu

SOLAR THERMOCHEMISTRY CONTEXT

- **Chemistry**: Making and breaking bonds
- **Thermochemistry** combines the concepts of thermodynamics with the idea of energy in the form of chemical bonds.
- **Thermochemistry** is a branch of **thermodynamics** that is the study of heat generated (exotherm) or consumed (endotherm) in a **chemical reaction**.
- **Solar**: Source of heat particularly to promote the endothermic reactions

Heat can also accelerate reactions even if exothermic

High temperature can be sustainable when enabled by solar fuels or concentrated solar

- **Deep Decarbonization:** Applications to a large range of carbon-intensive sectors
- **Dispatchability:** Enable deeper penetration of renewables with less curtailment

SOME (MANY) APPLICATIONS OF SOLAR THERMOCHEMISTRY

Thermochemical Storage	Solar Fuels	Commodities
Redox Cycles Hydration/ De-Hydration Carboxylation/ De-Carboxylation	Redox Cycles: Water and Carbon Dioxide Splitting Reforming/ Gasification Chemical Looping with CH_4	Redox Cycles: Air Separation Calcination Metal Ore Reduction
Heat for power cycles (air Brayton or sCO_2 Brayton) or other high temperature industrial processes	*Hydrogen (H_2), Carbon Monoxide (CO), Syngas (H_2/CO/CO_2 mix) Methanol (CH_3OH), DME (O=$(CH_3)_2$), Diesel, Jet Fuel, NH_3, Co-produce H_2 / e^-*	*Metals (Fe, Al, Zn, Cu, Li) Steel, Cement, lime, Pure Nitrogen (N_2), Pure Oxygen (O_2), Ammonia (NH_3)*

SOME THERMOCHEMICAL REACTIONS OF INTEREST

Redox: Oxygen Shuttle

$$\frac{1}{\delta}MO_x \rightarrow \frac{1}{\delta}MO_{x-\delta} + \frac{1}{2}O_2$$

$$CH_4 + \frac{1}{\delta}MO_x \rightarrow \frac{1}{\delta}MO_{x-\delta} + CO + 2H_2$$

$$H_2 + \frac{1}{\delta}MO_x \rightarrow \frac{1}{\delta}MO_{x-\delta} + H_2O$$

$$\frac{1}{\delta}MO_{x-\delta} + H_2O \rightarrow \frac{1}{\delta}MO_x + H_2$$

$$\frac{1}{\delta}MO_{x-\delta} + CO_2 \rightarrow \frac{1}{\delta}MO_x + CO$$

$$\frac{1}{\delta}MO_{x-\delta} + Air \rightarrow \frac{1}{\delta}MO_x + N_2$$

Thermochemical Energy Storage

$$\frac{1}{\delta}MO_x \rightleftarrows \frac{1}{\delta}MO_{x-\delta} + \frac{1}{2}O_2$$

$$CaCO_3 \rightleftarrows CaO + CO_2$$

$$Ca(OH)_2 \rightleftarrows CaO + H_2O$$

Thermochemical Ammonia

$$\frac{1}{\gamma}MN_x + \frac{3}{2}H_2 \rightarrow \frac{1}{\gamma}MN_{x-\gamma} + NH_3$$

$$\frac{1}{\gamma}MN_{x-\gamma} + \frac{1}{2}N_2 \rightarrow \frac{1}{\gamma}MN_x$$

Gasification

$$C_xH_{2y}O_z + (x-z)H_2O \rightarrow (y+x-z)H_2 + xCO$$

Reforming

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

$$CH_4 + CO_2 \rightarrow 2CO + 2H_2$$

Each application presents different challenges at the system level but many commonalities too

Important to co-optimize materials, reactors, desired operating range, and the systems

KEY RISKS OFTEN OVERLOOKED EARLY IN THE DEVELOPMENT PROCESS

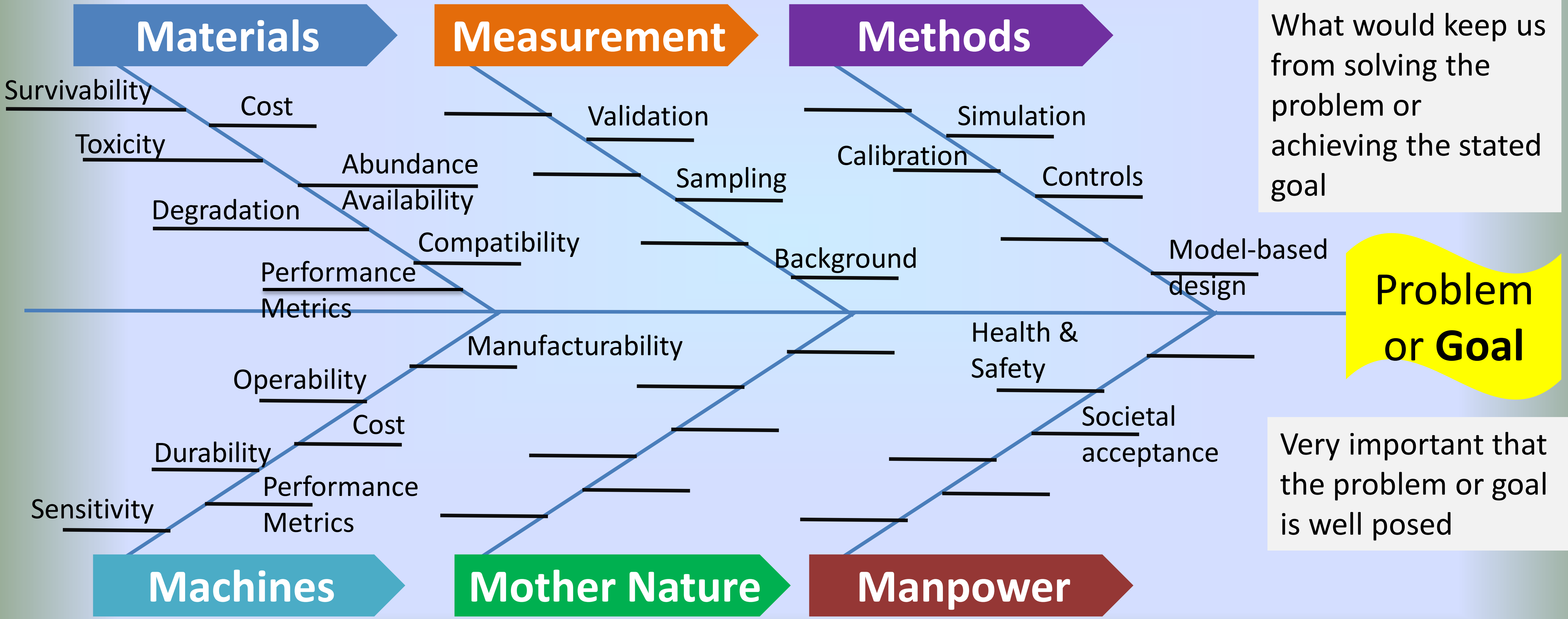
Having a good technical risk assessment and review formalism

- Identifying all the possible failure modes – what would keep the material, the functional components, interfaces, or the system from working as intended?

Potential Failure mode	Potential Effect(s) of Failure	Severity (1-10)	Potential Mechanism(Causes) of Failure Mode	Occurrence (1-10)	Current Design Features/ Controls	Detection (1-10)	Risk Priority Number (RPN)	Recommended Actions

- The FMEA (Failure Mode Effects & Analysis) is a collaborative exercise and works best with a diverse team
- Can be effective at identifying and mitigating or eliminating risks
- Applies broadly, e.g., to design of functional materials, components, interfaces, and the full system
- Early on – sufficient to drive the RPN = Severity × Occurrence × Detectability < 100

FISHBONE DIAGRAM CAN AID IN ASSESSING RISKS

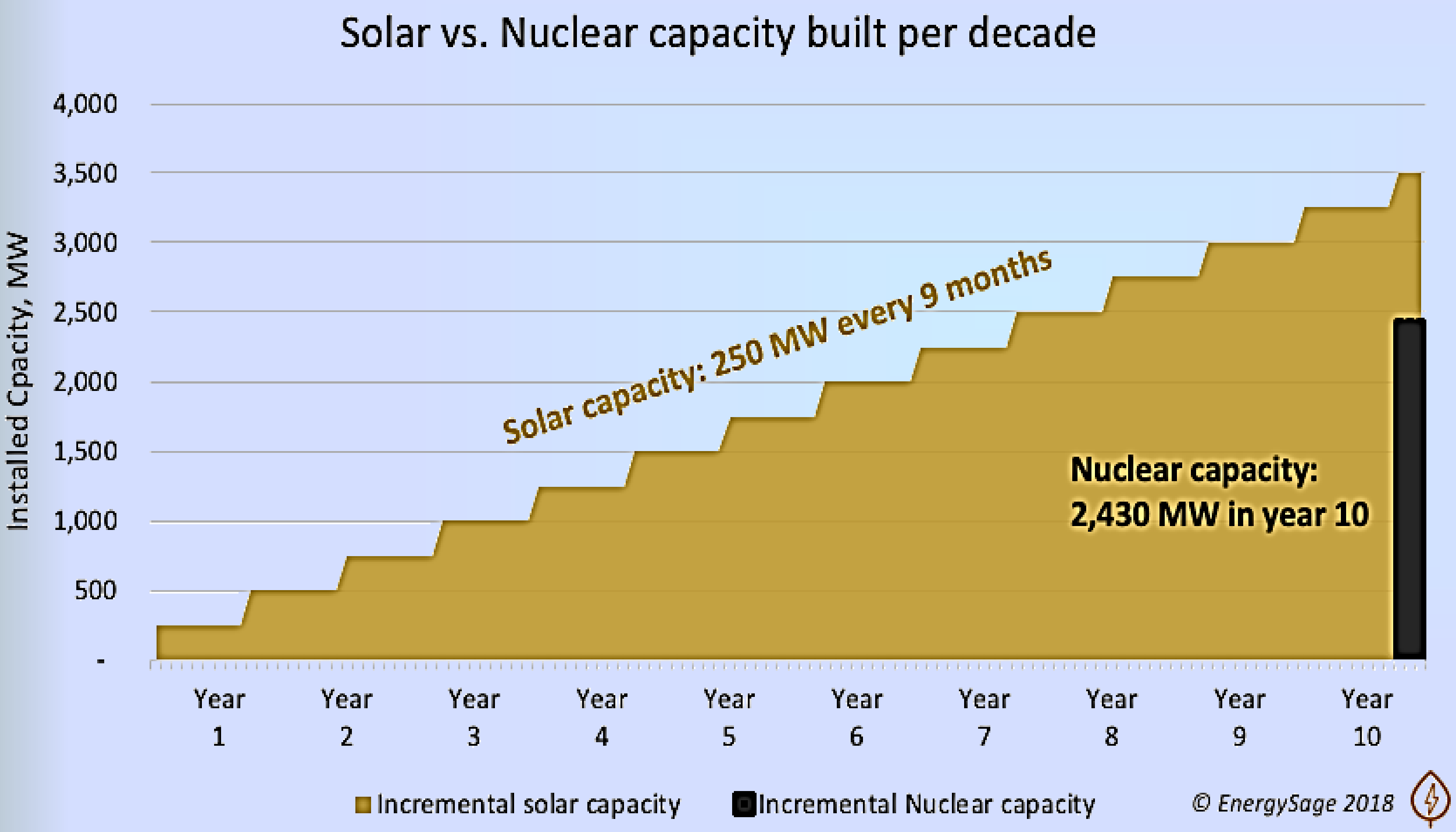


What would keep us from solving the problem or achieving the stated goal

Very important that the problem or goal is well posed

ASU LightWorks
ARIZONA STATE UNIVERSITY

VERY IMPORTANT RISK IS GETTING THE SCALE RIGHT



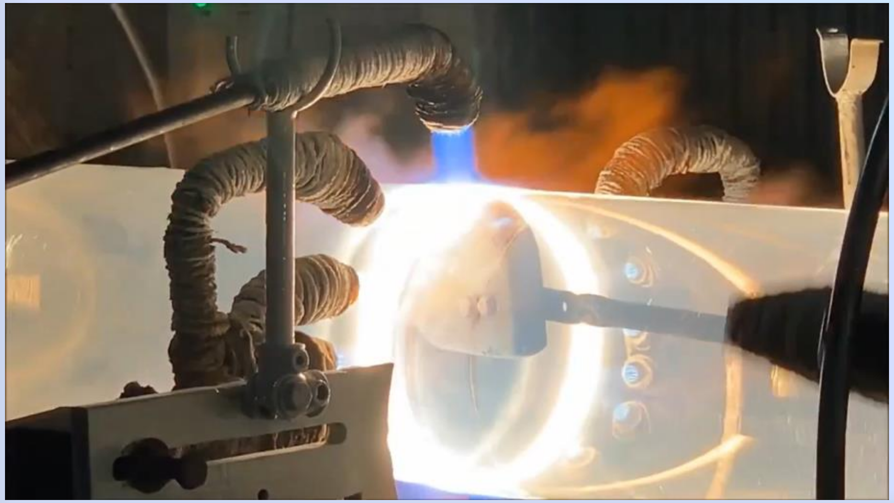
- Flexibility, Adaptability
- Faster Learning
- Less Investor Risk
- Start generating revenue more quickly
- Matching scale with downstream processing, e.g., syngas → jet fuel

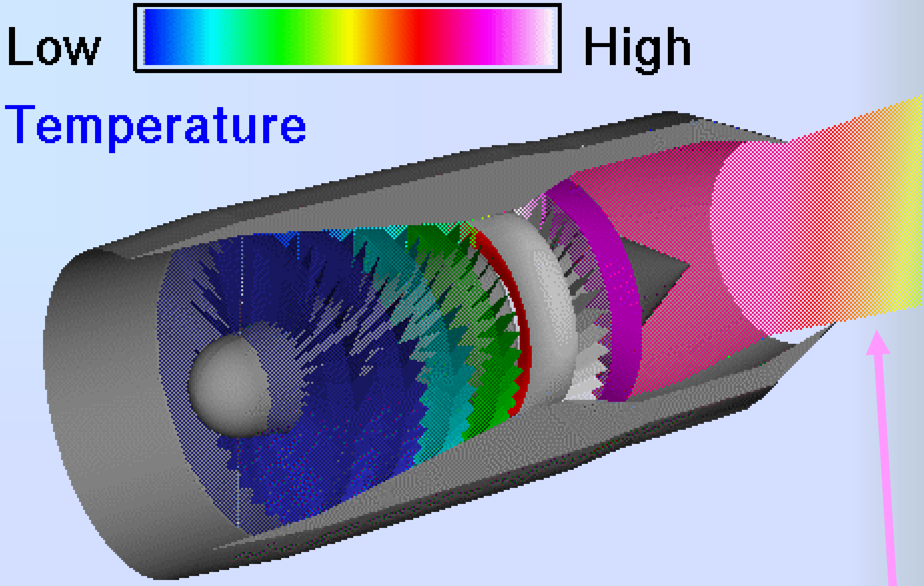
RISK OF NOT OPTIMIZING FOR THE THERMODYNAMICS BECAUSE OF HIGH TEMPERATURE

Challenging but not necessarily a show-stopper: Know the difference between an engineering challenge that might have analogs in other applications and show-stoppers

High Temperature Industrial Processes

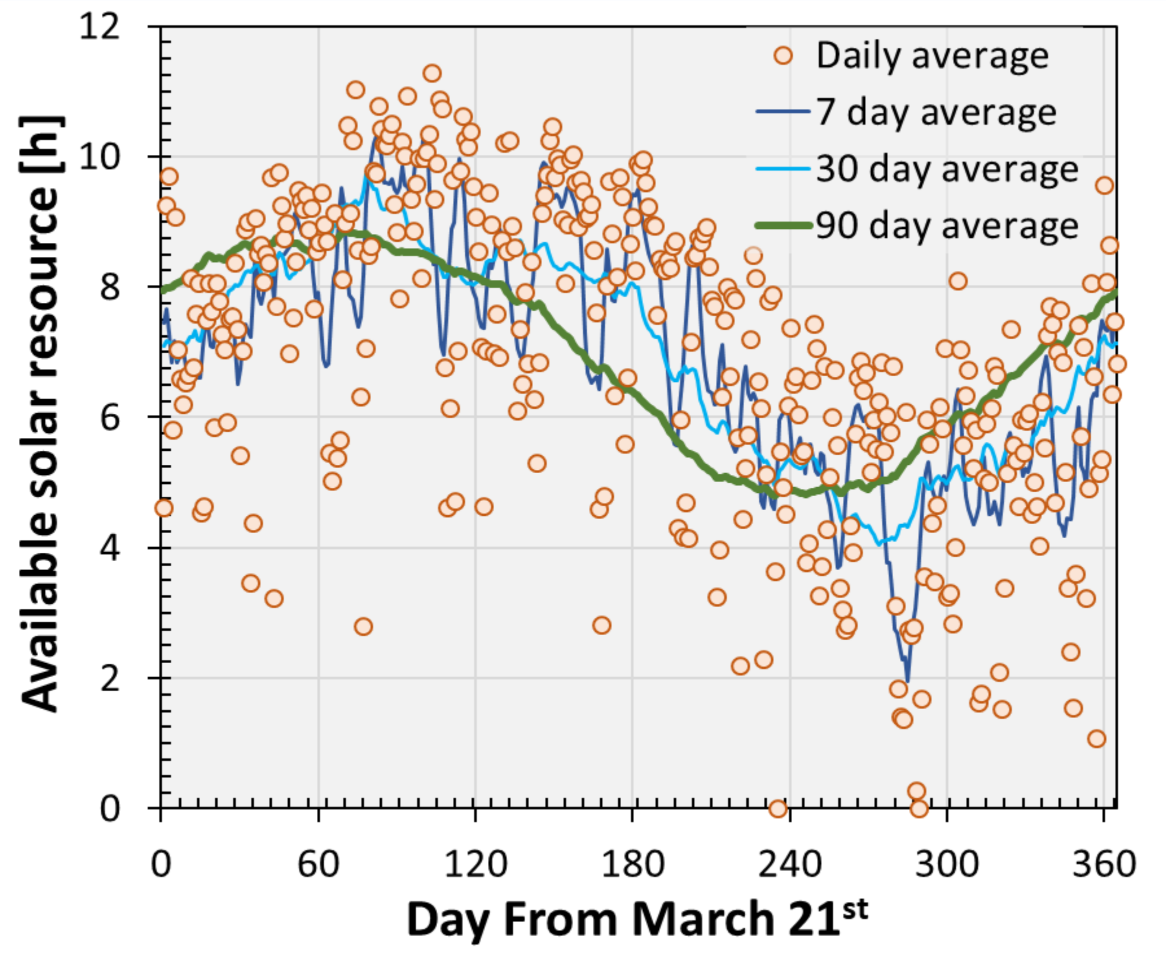
Fusing quartz under H_2/O_2 flame: T~1700°C





Jet turbine inlet temperature: ~1600°C

REGIONS WITH AN EXCELLENT SOLAR RESOURCE STILL MUST COPE WITH SUBSTANTIAL VARIABILITY



- Must consider the impact of the variability
- Determine performance off design point
- Might have both supply and demand variability (as with electricity).
- There may be consequences for downstream (off-sun) processes to consider

COST DRIVERS ARE TECHNICAL METRICS IMPORTANT AT ALL PHASES OF DEVELOPMENT

- Total Project Investment or CAPEX: $Cx\ (\$/kW)$
- Capacity Factor: CF (Between 0 and 1)
- Energy Utilization: $eU\ (kWh/kg)$ ∝ 1/Efficiency
- Cost of energy plus variable O&M: $Ce\ \$/kWh$
- Annualized cost factor (financial plus fixed O&M): $crf\ \left(\frac{1}{yr}\right)$

$$\frac{\$}{kG_{Product}} = eU \times \left\{ \frac{Cx \times crf}{CF \times 8760\ hr/yr} + Ce \right\}$$

Power Density: kW/L
Measure of compactness

Balancing solar constraints and balance of system – won’t necessarily eliminate cost of energy

May not match up on CF either

Acknowledgments

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Work is funded in part by the U.S. DOE SETO

Award Number 08991 Weekly and Seasonal Storage

- ASU, Siemens Corporation, U. of Oregon, Sandia National Labs, and Southwest Research Institute
- DOE Project Manager: Matthew Bauer

Award Number 34250 Solar Thermochemical Ammonia Production

- Sandia National Labs (SNL), ASU, and Georgia Institute of Technology
- DOE Project Manager: Levi Irwin

HydroGEN
Advanced Water Splitting Materials

Work is funded in part by the U.S. DOE FCTO

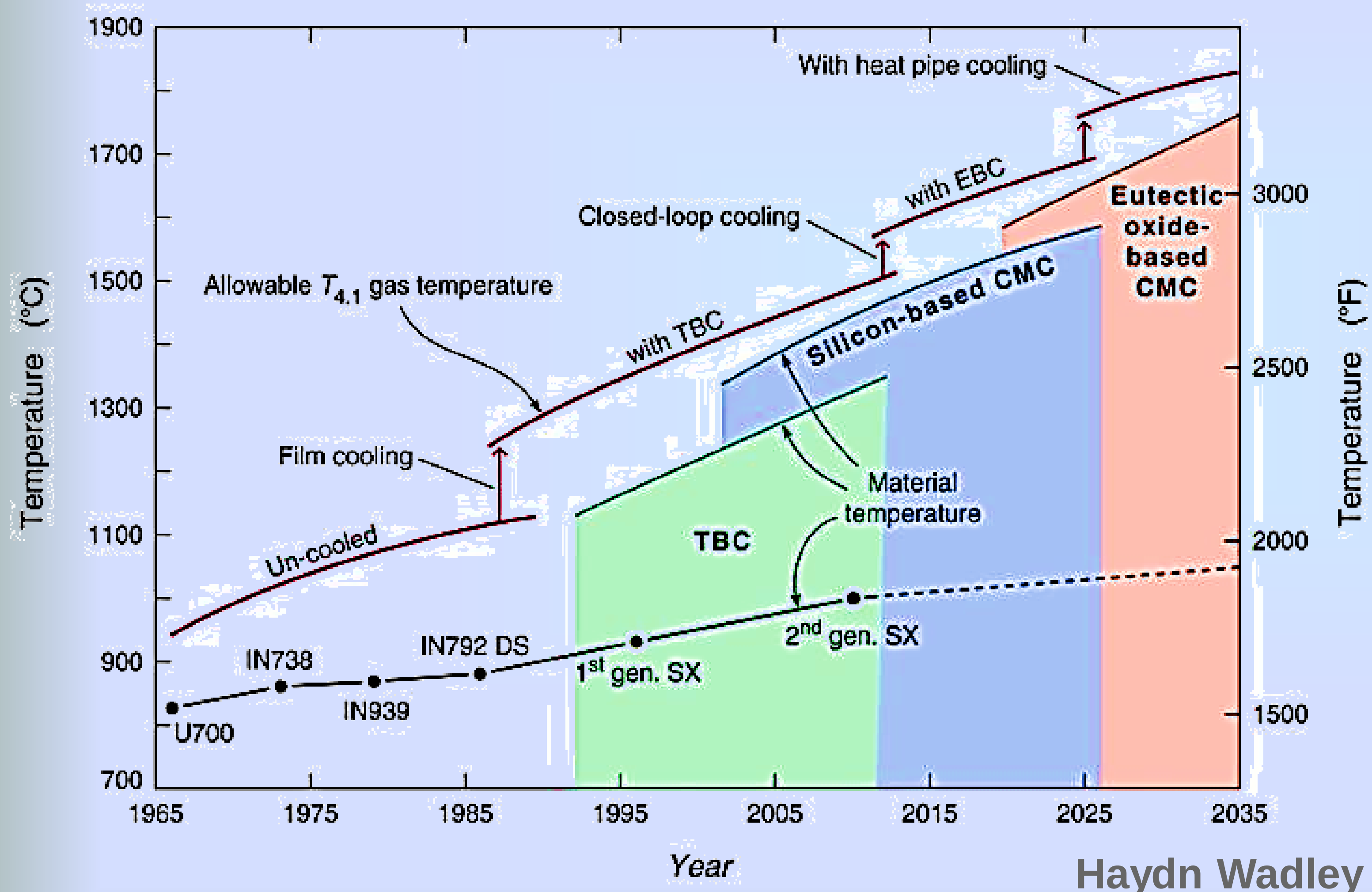
Award Number 08090 Materials Discovery
Solar thermochemical water splitting

- ASU and Princeton (collaborative support from SNL and NREL)
- DOE Project Manager: Katie Randolph

Award Number 08090 Materials Discovery – Solar thermochemical water splitting

- Nel Hydrogen, ASU, Caltech, and PNNL
- DOE Project Manager: Katie Randolph

INLET TEMPERATURE ON JET ENGINES CONTINUOUSLY INCREASING



Haydn Wadley

The evolution of allowable gas temperature at the entry to the gas turbine and the contribution of superalloy development, film cooling technology, thermal barrier coatings and (in the future) ceramic matrix composite (CMC) air foils and perhaps novel cooling concepts.

Unlocking Solar Thermochemical Potential: Markets, Opportunities, and Challenges

Workshop – November 12^{th}, 2020

Dr. Davide Zampini

Head of CEMEX Global R&D

GLOBAL research & development CEMEX

CEMEX – GLOBAL CONSTRUCTION MATERIALS

Cement

Aggregates

Ready-Mix

● CEMEX OPERATIONS ● A GLOBAL TRADING NETWORK

NET SALES	13,130
EBITDA	2,378
FREE CASH FLOW	695

Millions USD

Urbanization Solutions

Sustainability

Admixtures

cemex

GLOBAL research & development

CEMEX

CEMENT AND GRINDING PLANTS **65**

MILLION TONS PRODUCTION CAPACITY **93**

CEMENT

QUARRIES **262**

MILLION TONS ANNUAL SALES VOLUME **135**

AGGREGATES

+40.6 THOUSAND EMPLOYEES

PEOPLE

1,427 PLANTS

50 MILLION m^3 ANNUAL SALES VOLUME

READY-MIX CONCRETE

279 LAND DISTRIBUTION CENTERS

56 MARINE TERMINALS

TERMINALS

CEMEX – CLIMATE ACTION

Target 2030:

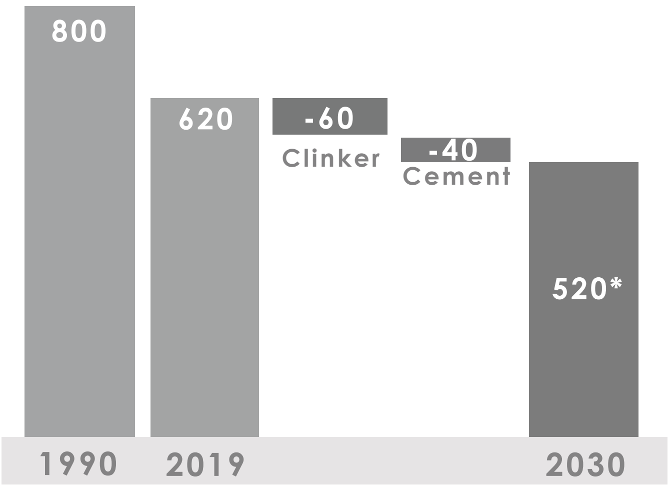
Cement

35%

Reduction of CO_2 Emissions vs 1990 Baseline

Aligned with the 2 Degree scenario of the IEA

kgCO_2/ton cementitious



Proven technology, focus on fast deployment and removing barriers

Ambition 2050:

Concrete

Net-zero CO2 Concrete Globally

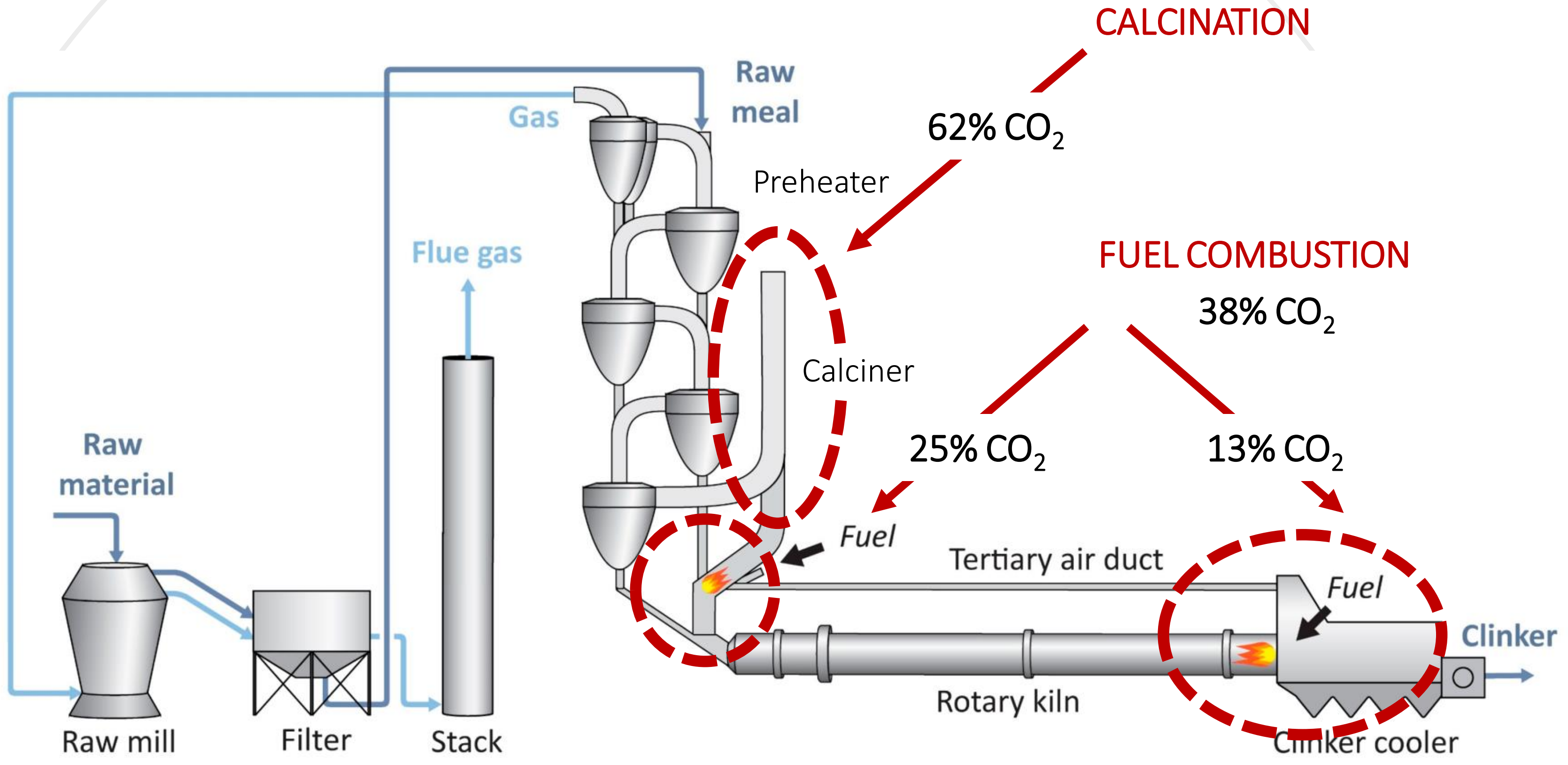
Estimated CO2 Footprint for a high strength concrete produced with cement Type I

A significant portion of CO_2 mitigation (> 30%) will rely on technologies not yet fully developed – not industrially and commercially viable. Innovation / R&D.

CEMEX

GLOBAL research & development

CLINKER MANUFACTURING PROCESS



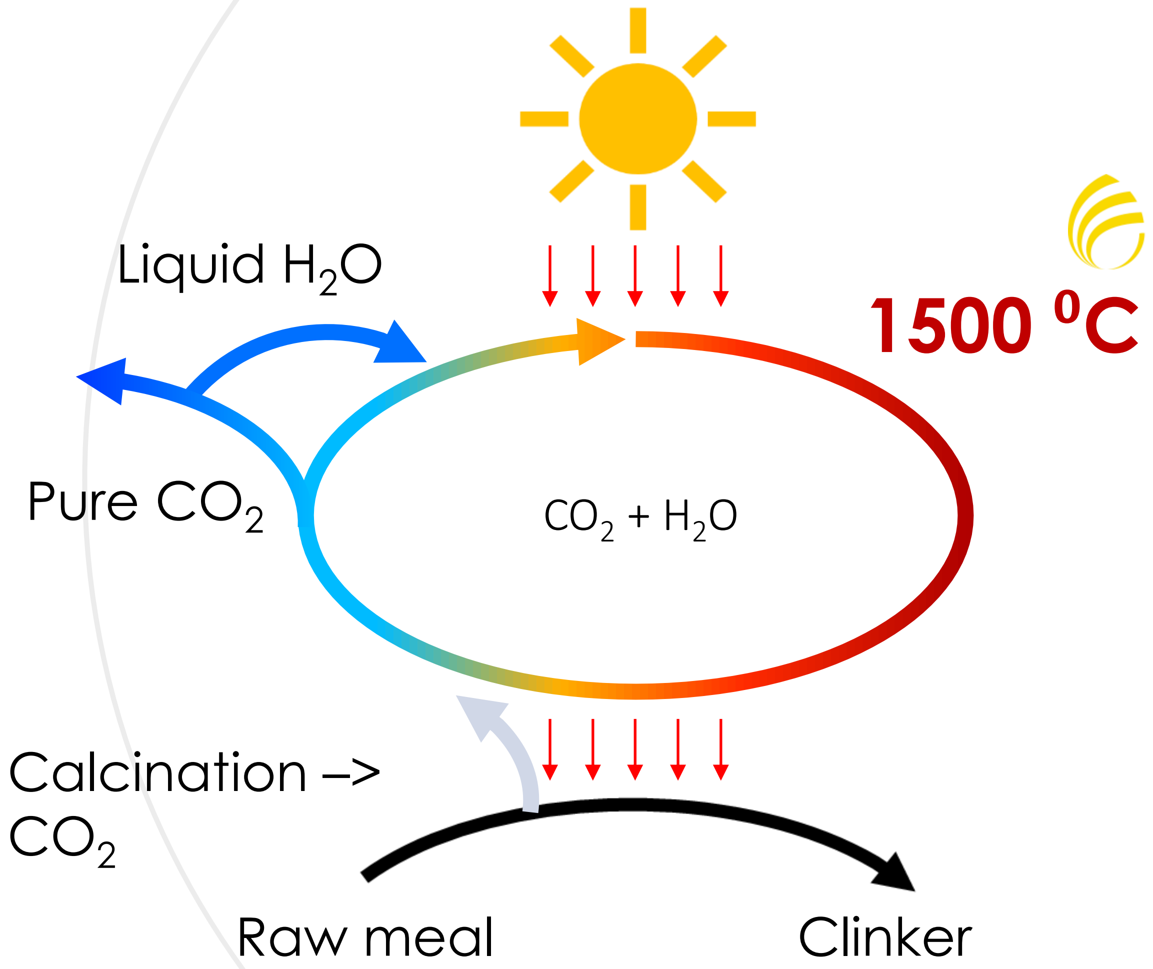
CHALLENGES

- CO_2 Reduction
- CO_2 Concentration & Capture
- CO_2 Reutilization

Cement Manufacture Diagram - Pires, J.. (2019). Carbon Capture and Storage.

SOLAR-DRIVEN PYRO-PROCESSING OF CLINKER

High Performance High Temperature Solar Heat & Thermo-Chemical Processes



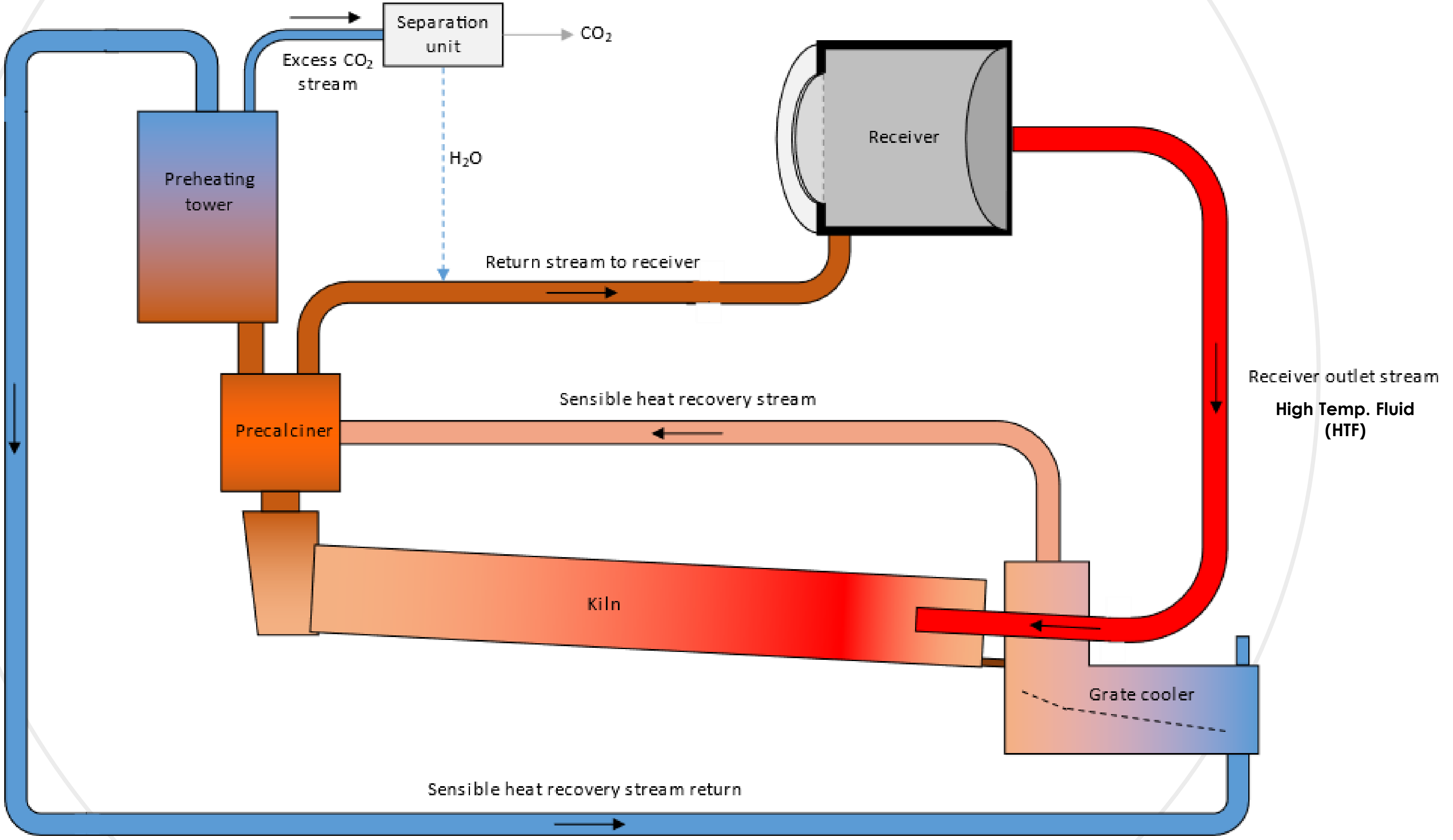
Synhelion

- **DRIVE FULL PROCESS WITH SOLAR ENERGY** in-line with conventional process flow
- **NO** CO_2 emissions
- **NO** fuel costs

CEMEX

GLOBAL research & development

High Level Conceptualization – Inspiration of the Aspiration



CLOSING THE CARBON CYCLE

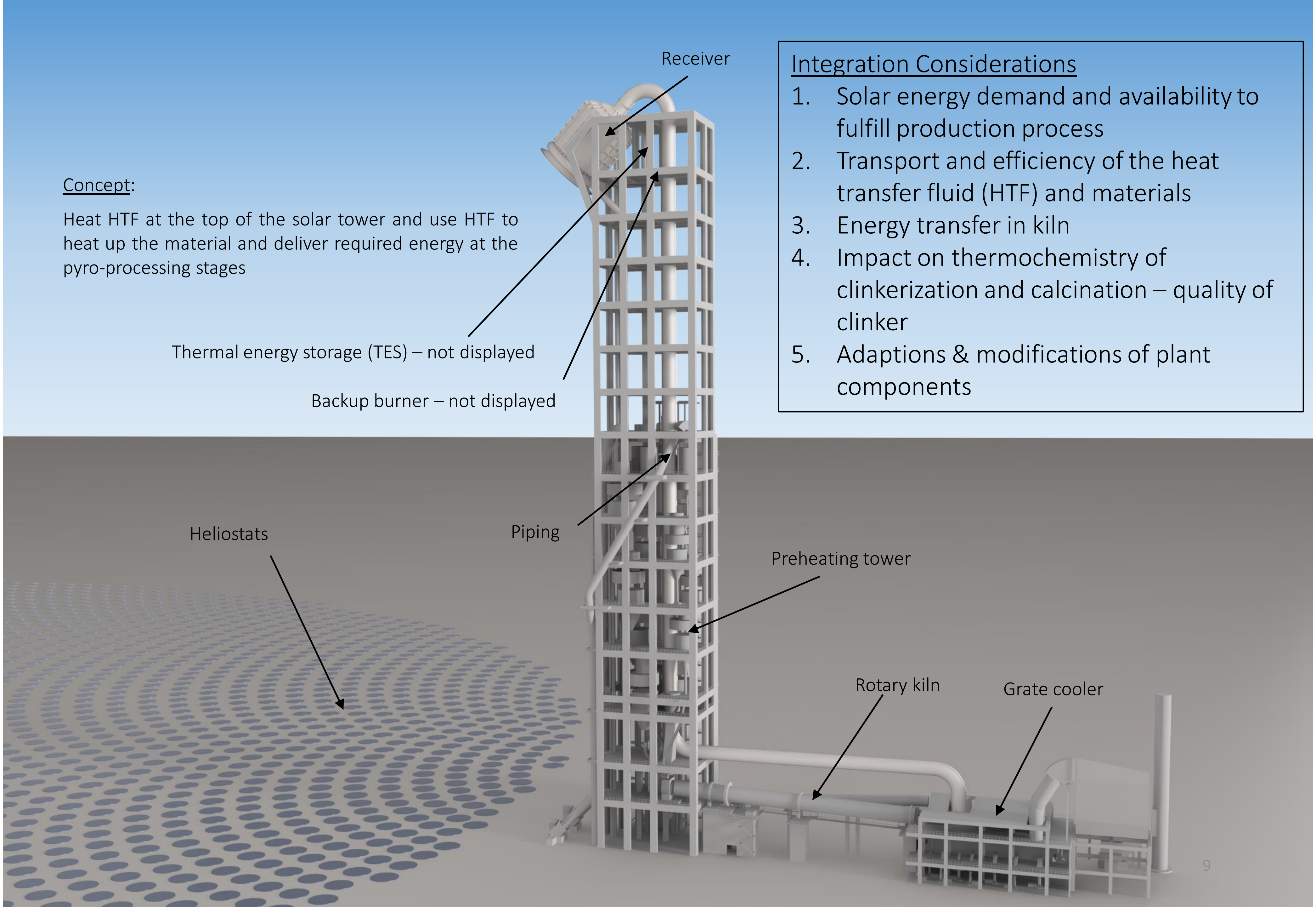
CEMEX

GLOBAL
research & development

INTEGRATION CHALLENGES

Concept:

Heat HTF at the top of the solar tower and use HTF to heat up the material and deliver required energy at the pyro-processing stages



Integration Considerations

1. Solar energy demand and availability to fulfill production process
2. Transport and efficiency of the heat transfer fluid (HTF) and materials
3. Energy transfer in kiln
4. Impact on thermochemistry of clinkerization and calcination – quality of clinker
5. Adaptions & modifications of plant components

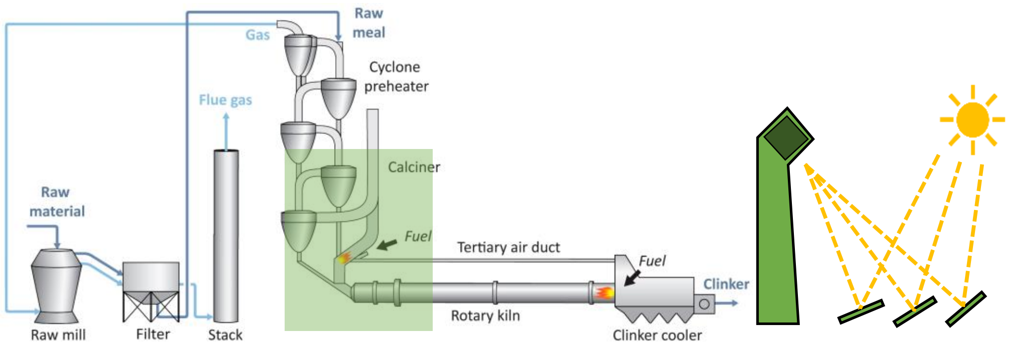
CEMEX

INTEGRATION: STEP-WISE HYBRIDIZATION

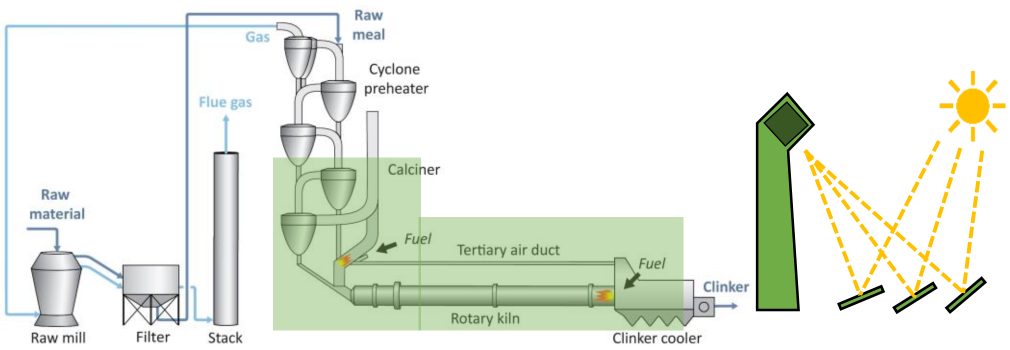
CONFIGURATION

INTERVENTION SCHEME

Solar Calcination →



Full Solar →



2021
Calcination “Lab” Pilot
250kW$_{th}$

2023
Calcination Pilot
1 MW$_{th}$

Full Solar
1 MW$_{th}$

2026
Full Integration
10 MW$_{th}$

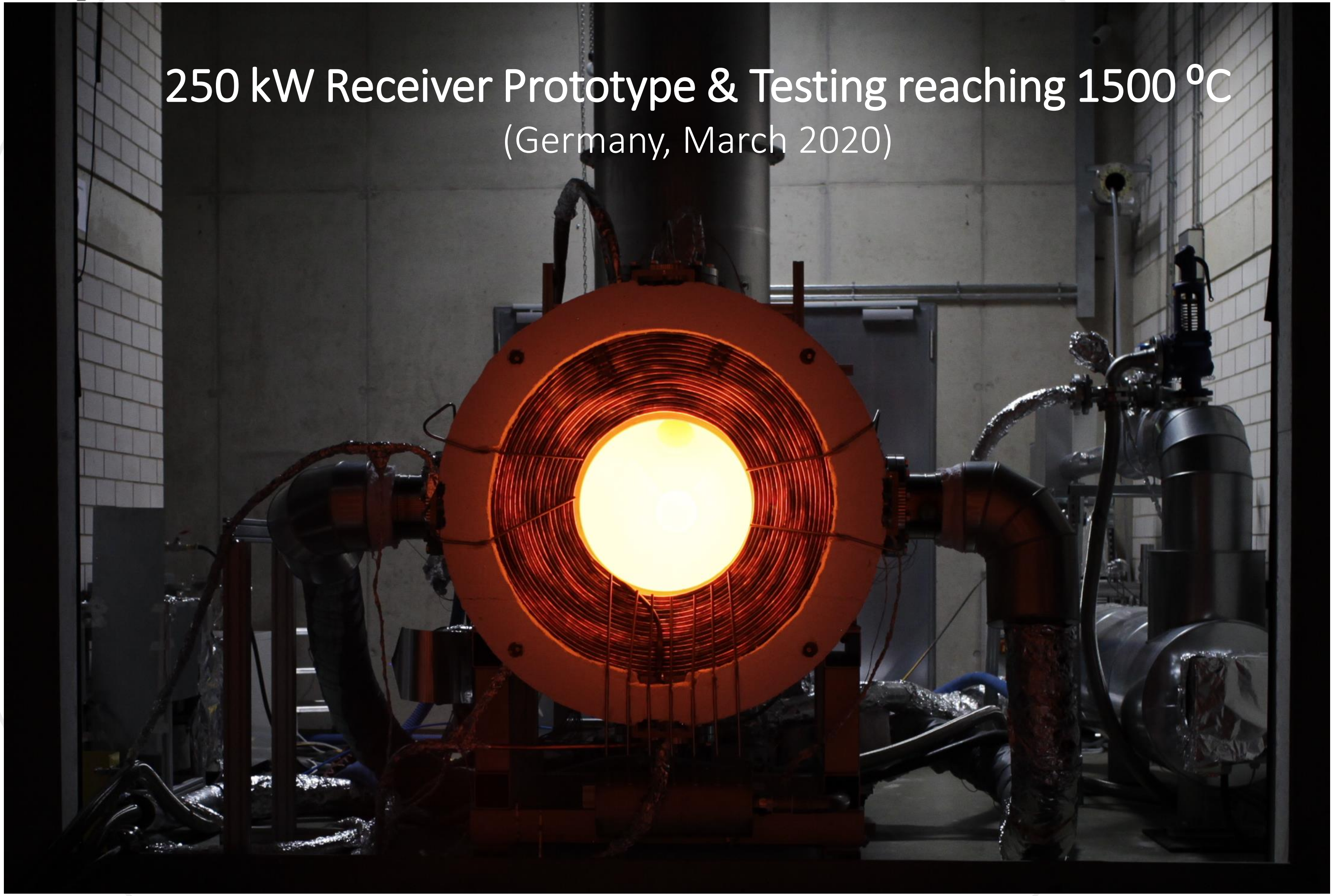
2028
Industrial Scale
100 MW$_{th}$
600 tpd

CEMEX

GLOBAL research & development

TECHNOLOGICAL VALIDATION – KEY MILESTONES

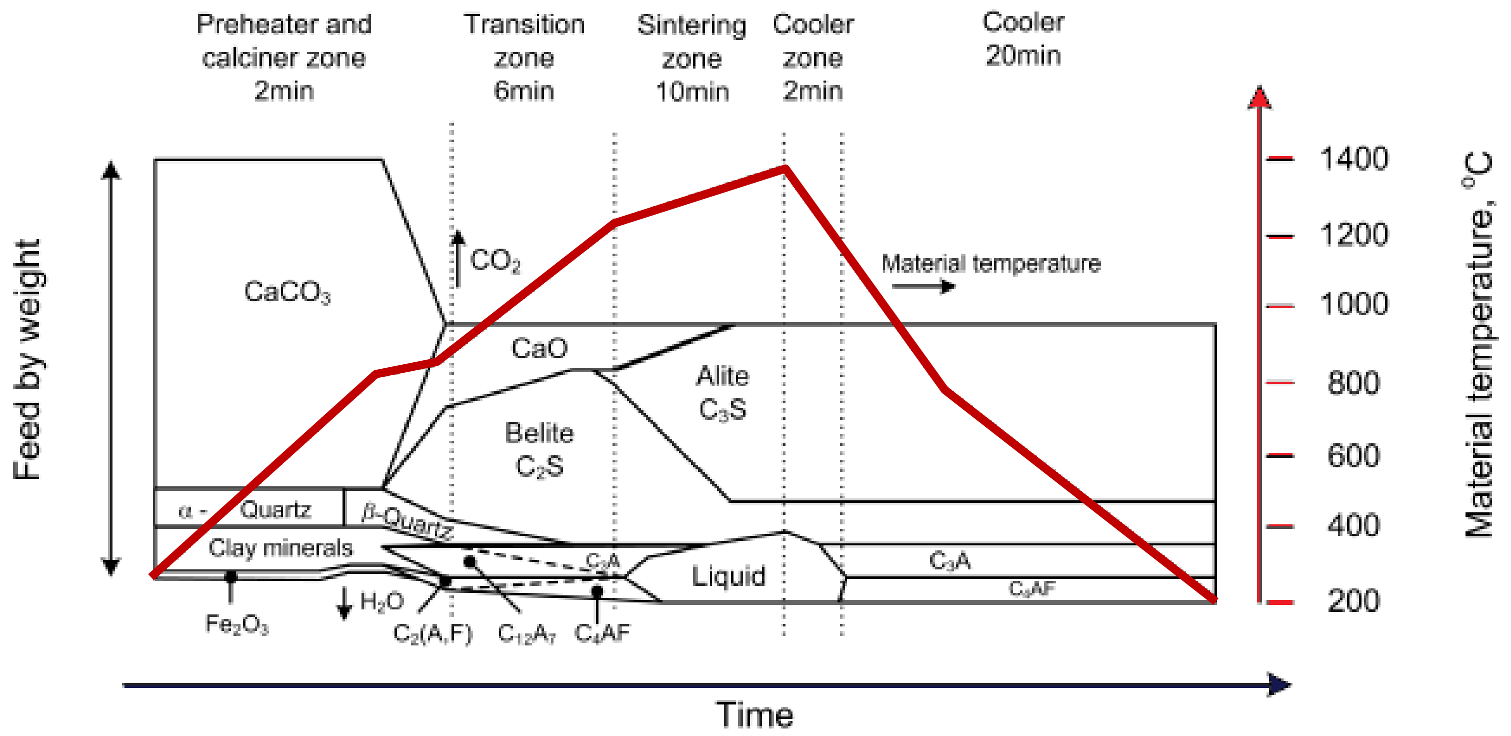
Synhelion



TECHNOLOGICAL VALIDATION – KEY MILESTONES

HTF CLINKERIZATION AND CALCINATION

Material Quality & Performance Unaltered



- Impact of the Heat Transfer Fluid (HTF) on the heating zones including residence time
- Heat exchange efficiency between material as a function of CO_2/ H_2O ratios
- Shifts of heating curves and phases formation

* Nørskov, L. K., Dam-Johansen, K., Glarborg, P., Jensen, P. A., & Larsen, M. B. (2012). Combustion of solid alternative fuels in the cement kiln burner. Kgs. Lyngby: Technical University of Denmark (DTU).

CEMEX

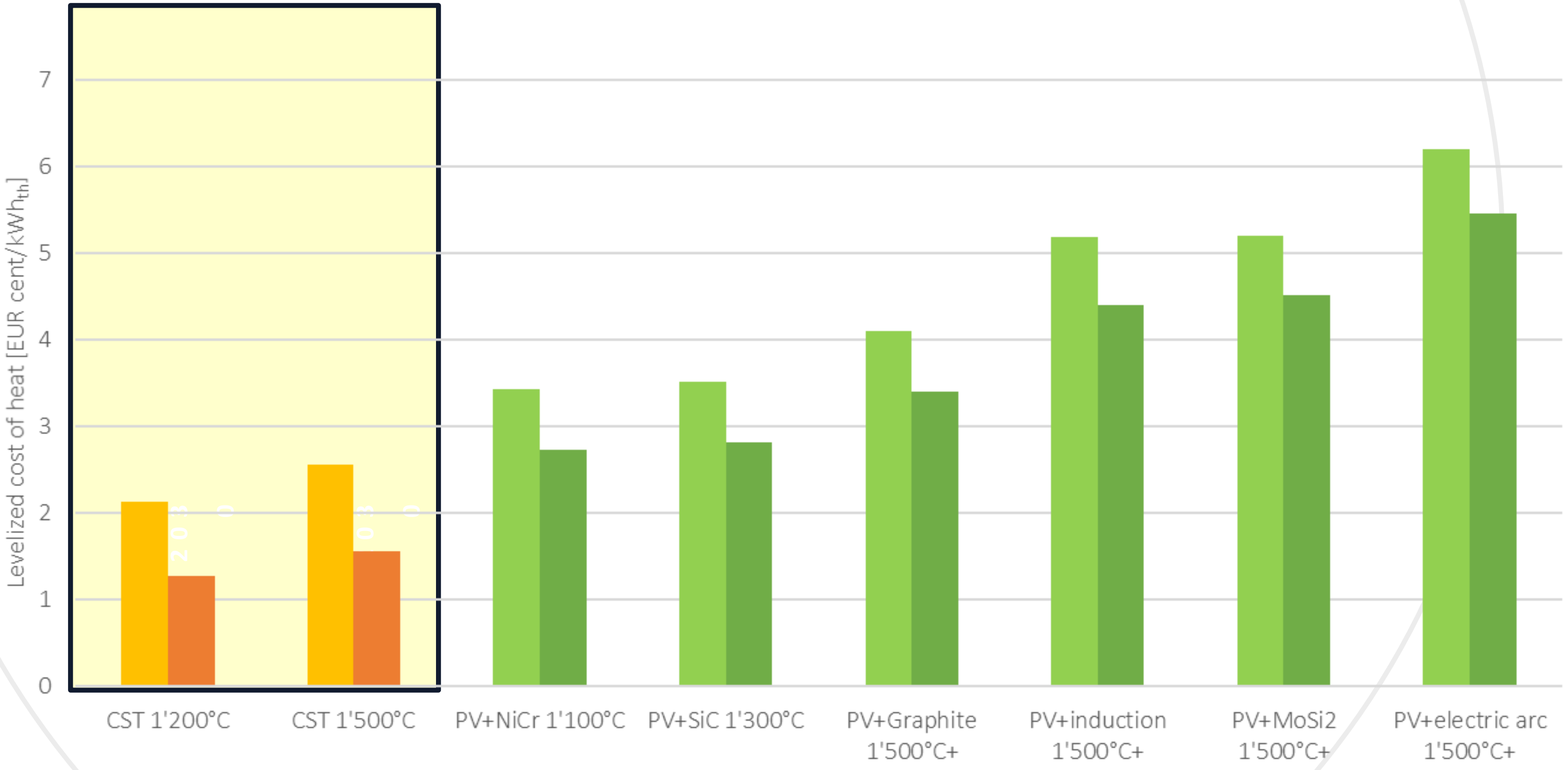
GLOBAL research & development

BACK UP

SOLAR HEAT vs OTHER SOURCES

WHY CST (SOLAR THERMAL) - COST OF HEAT

While there is a growing interest in electrically heated systems driven directly by cheap renewable power as alternative to CST systems, even under very aggressive conditions CST has the upper hand.



26th SolarPACES Conferenc – Plenary: Green Hydrogen, "Solar thermal pathways for renewable hydrogen and fuel," Gianluca Ambrosetti, Synhelion

CEMEX

GLOBAL research & development

Predicting the Future: Evaluating Technology through Dynamic Stochastic Economic Modeling

(or: why engineers and economists need to talk)

Peter Pfromm

School of Chemical Engineering and Bioengineering

Washington State University

Vincent Amanor-Boadu

Department of Agricultural Economics

Kansas State University

This should never be applied to fundamental research, unless "cheaper" "more efficient" etc. is claimed.

Dynamic Predictive Technology Modeling: Approach

Preferably prior to or at most in parallel to any laboratory/bench/pilot research

It is not acceptable to avoid this by saying that research/development must be done first, then the promising impact will be shown later. Overall economics (including feedstocks, non-ideal conditions, waste treatment, public opinion, politics, policies...) are to be shown first IF the "cheaper/more efficient" argument is used. Capex/Opex is never sufficient.

Process Engineering

Material- and Energy Balances

Spreadsheet based
Steady State process modeling,
Aspen Plus

as needed: Aspen Dynamics

Math: systems of algebraic (steady state) or differential (dynamic) equations

Economics

Dynamic economic simulation
define sources, sinks, processes, markets, tax/government support, relationships, set up Stella model

Math: systems of differential equations

Team:
Engineers and economists are required, scientists as needed.

Dashboard type live dynamic what-if, scenarios:
Policy changes, market changes, technology improvement, impact of discoveries

Audience: Industry, venture capital, government agencies, your research group

Decisions

no go

go

fund research, invest, plan work ...

Dynamic Predictive Technology Modeling
Success Stories

Bio-Butanol, 2010:
predicted that no fuel bio butanol will be produced, also predicted fuel bio ethanol return to positive territory in 2014
Proof: no fuel butanol industry emerged. Fuel bioethanol returned to profitability as predicted.

Fuel from algae, 2011:
predicted that no success is possible without very substantial government support.
Proof: no algae fuel is being produced.

Renewable Solar Thermochemical Ammonia, 2012:
Work was started with dynamic predictive modeling, not lab work. The technology approach appeared reasonably competitive with state of the art natural gas based ammonia even with no benefit from avoiding fossil CO_2.
Proof: substantial industry- and government funded work towards renewable ammonia is in progress globally (electrolytic hydrogen production is currently favored). Renewable ammonia will first be used to decarbonize shipping, with outlook to use it as a hydrogen vector.

Ongoing:

Small Scale Renewable Ammonia from Wind:
Under way, via NSF INFEWS project. Viability of small scale renewable ammonia synthesis in the Midwest U.S. is the focus. Engineering is ready to be integrated into dynamic economic modeling.
Engineering economics (capital & operating cost) look promising, dynamic economic modeling will show overall viability.

CONCENTRATED SOLAR POWER CHEMICAL USE CASES:

HYDROTHERMAL PROCESSING

HYDROGEN PRODUCTION

Unlocking Solar Thermochemical Potential: Markets, Opportunities, and Challenges

Concentrating Solar Power Program
United States Department of Energy
Solar Energy Technologies Office

November 12, 2020

SoCalGas A Sempra Energy utility®

CSP Driven
Hydrothermal Processing

Hyperlight Hylux™
Linear Fresnel Concentrated Solar Power System

From 2016 – 2019, SoCalGas collaborated with the California Energy Commission and the U.S. Department of Energy in supporting the development and demonstration of **Hyperlight Energy's** novel, **low-cost** linear Fresnel CSP system (**Hylux™**)

Motivation: Demand for a CSP system that can be competitive with low-cost North American natural gas

Linear Fresnel Primary Solar Receiver

(Delegates From Energir, GRDF, GRTgaz, SoCalGas)

The **Hylux™ primary receiver** consists of mirrors attached to "D-shaped" PVC tubes

The tubes are supported by water contained in a polymer "pond-liner" material, framed by rebar cages

Thus, the structural materials are inexpensive:

- **Water**
- **Plastic**

Linear Fresnel Primary Receiver Control Mechanism

The **Hylux™** primary receiver tracks the sun using a simple computer-controlled, off-the-shelf actuator

Linear Fresnel Secondary Receiver

The **Hylux™ secondary receiver** consists of a stainless steel pipe containing thermal oil, inside a carefully designed evacuated reflective parabolic concentrator

Secondary receiver papers published as a result of this project by the Thermal Systems Group, National Renewable Energy Laboratory (NREL), Golden, CO, USA:

- Evaluation and comparison of an adaptive method technique for improved performance of linear Fresnel secondary designs, Applied Energy (2017) Madeline Hack, Guangdong Zhu, Tim Wendelin
- New adaptive method to optimize the secondary reflector of linear Fresnel collectors, Solar Energy, (2017) Guangdong Zhu

Thermal Oil Control Valves and Heat Exchanger

Thermal Oil Control Valves, Heat Exchanger & Reservoir

Containerized Hydrothermal Processing System

Onsite tests with various wet biomass wastes—e.g. dairy cow manure

HTP Output Products

Solids with Phosphorus

HTP Oil

Water

RIN & LCFS Eligible

Highlights from a recent project proposal based on Hylux™ Current Cost/Performance)

Application: boosting a geothermal power plant, direct heating of geothermal produced fluid. Very simple integration, no heat exchanger. Carbon steal heat collection elements with geothermal fluid passing through directly.

Project size:

- 50 Hylux™ units
- ~25 acres
- ~30 MW_t

Project lifetime: 25 years

Estimate of LCOH: $3.50/MMbtu

Hylux™ CSP System Cost (price per m²)

	No ITC	22% ITC
Collector	$82	$64
Receiver	$57	$44
Solar field	$139	$108

CSP Driven
Hydrogen Production

STARS Hydrogen Generation

Solar Thermochemical Advanced Reaction System

Cost of H_2

- Current Cost in California: ~$14-16/kg at pump
- STARS Production Cost: ~ $2-3/kg based on low-to-moderate volumes of hardware mass production

Efficient Use of Solar Energy

- STARS: 70% World Record Solar-to-Chemical Energy Efficiency (Demonstrated)
- Solar PV + Electrolysis: ~16%

Carbon Intensity (CI) of H_2 Product

- STARS: ~60 g CO_2/MJ based on fossil NG with solar augment
- Both Cases with All-Renewable Resources (Renewable NG, Renewable Electricity & Solar): ~0 g CO_2/MJ
- STARS pathways have not yet been certified by CARB

Methane-Steam Reforming is Augmented with Concentrated Solar (Thermal) Energy

$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$

STARS Compact SMR

This is our compact steam-methane reformer.

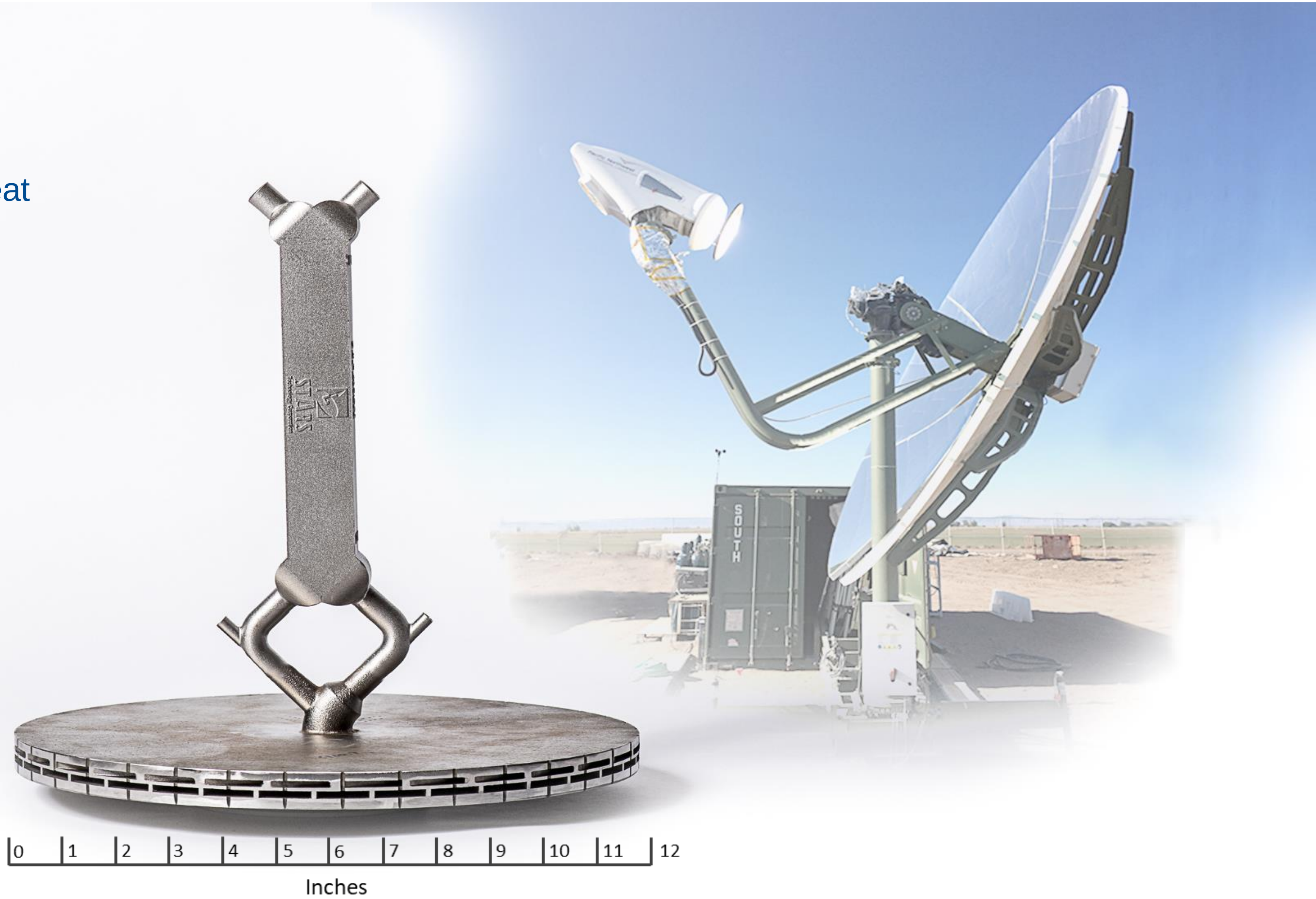
It’s a 3D printed microchannel chemical reactor with a 3D printed microchannel heat exchanger.

It can operate on solar-thermal or electric induction heating, or both.

In our tests, we achieved over 70% efficiency in converting solar energy into chemical energy.

This was developed by DOE and Pacific Northwest National Laboratory in collaboration with SoCalGas and others.

A laboratory spin-off: Stars Technology Corporation is leading the commercialization efforts.



One more thing…

Opportunity:
Repurposing Existing Solar Dish Concentrators

Tooele Army Depot, Utah

432 Dish Concentrators at Tooele Army Depot, Utah

Could they be repurposed for hydrogen production?

These Infinia PD-4 dish concentrators once powered Stirling heat engines

They could be adapted for the purposed of solar SMR hydrogen production

Heliogen

Replacing Fuels with Sunlight

Vikas Tuteja

Chief Operating Officer

November 2020

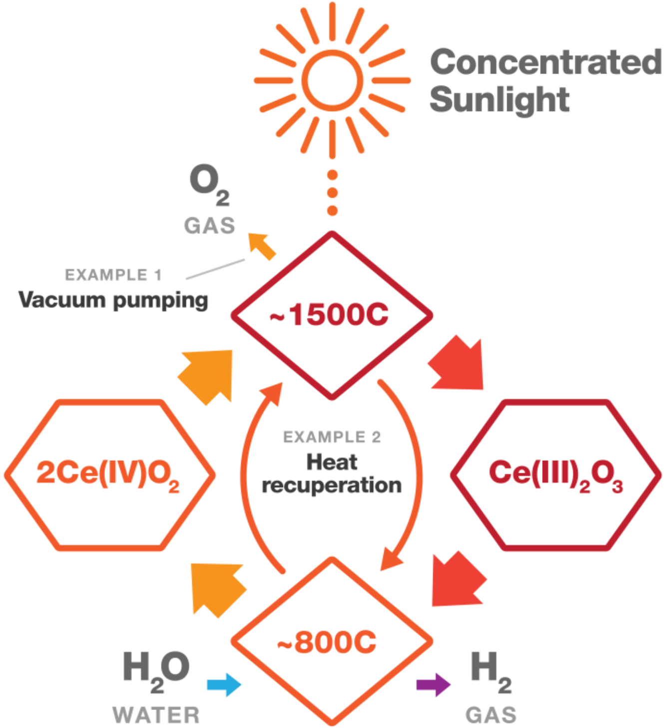
About Heliogen

24/7 low-carbon energy from the sun

- High concentration ratios through closed loop control
- Generation of carbon-free, ultra-high temperature heat
- Receivers and storage to match
- Integrated with industrial processes

Heliogen's facility in Lancaster, California

Solar Thermochemical Hydrogen



REDUCTION

$$2Ce(IV)O_2 \rightarrow Ce(III)_2O_3 + \frac{1}{2}O_2$$

OXIDATION

$$Ce(III)_2O_3 + H_2O \rightarrow 2Ce(IV)O_2 + H_2$$

NET REACTION

$$H_2O \rightarrow \frac{1}{2}O_2 + H_2$$

Insights + Recommendations

Advancing Industry

- Insist on a systems examination first using a common set of assumptions
- Identify individual areas of risk
- Fund research across all areas of risk, not just the “exciting” ones
- Expand research into thermoelectrochemical cycles

Thank You

Vikas Tuteja

Chief Operating Officer

vikas@heliogen.com

Spinoff ETH zürich

Synhelion solar fuels

THE PATH TOWARDS AFFORDABLE CLEAN FUELS

12.11.2020, DOE Webinar-Workshop

SYNHELION TECHNOLOGY – THE VISION

Click here or scan the QR code to watch the video.

Click here or scan the QR code to watch the video.

SYNHELION TECHNOLOGY – THE WAY TO MARKET

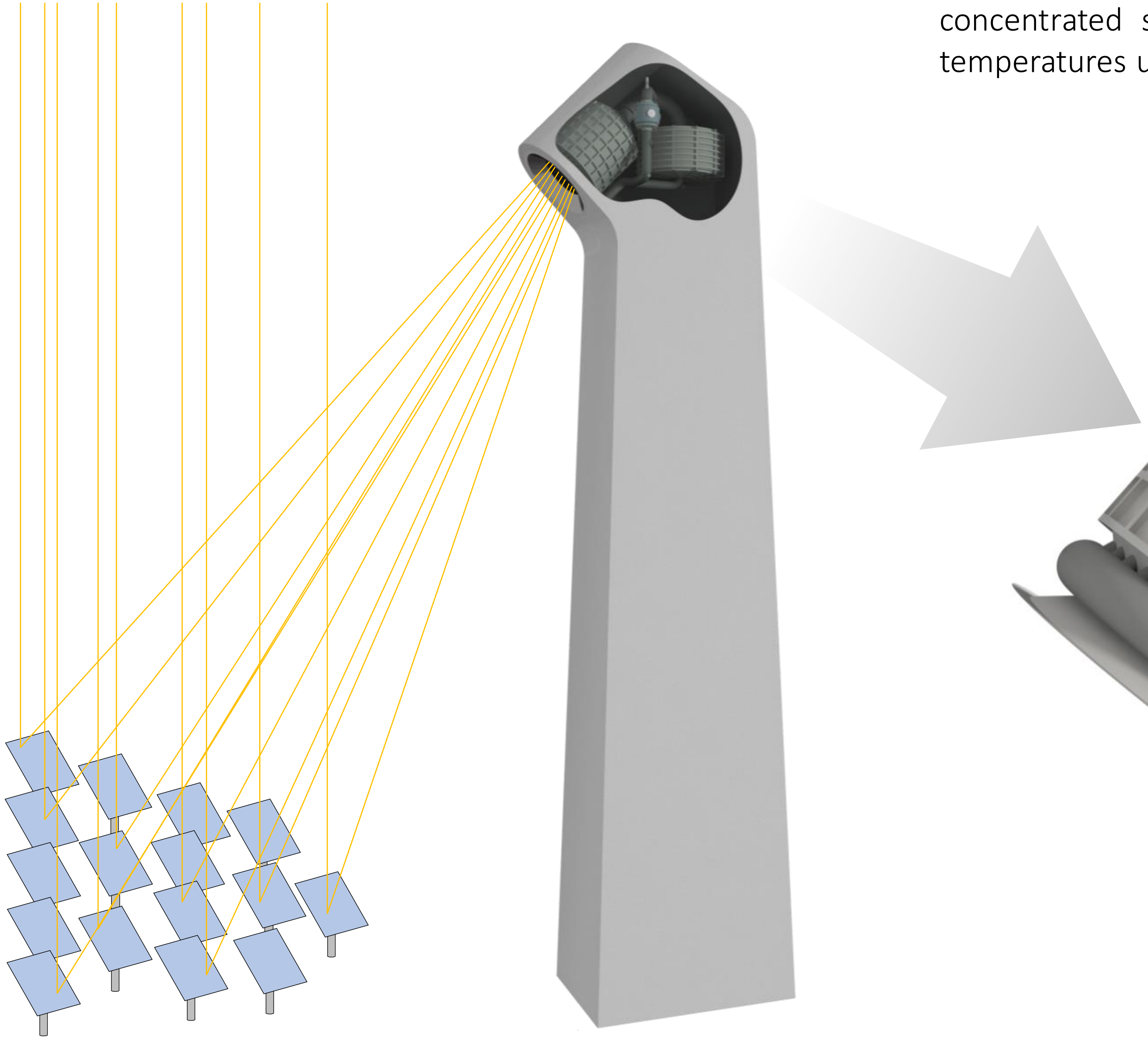
First to market **solar upgrading** process:

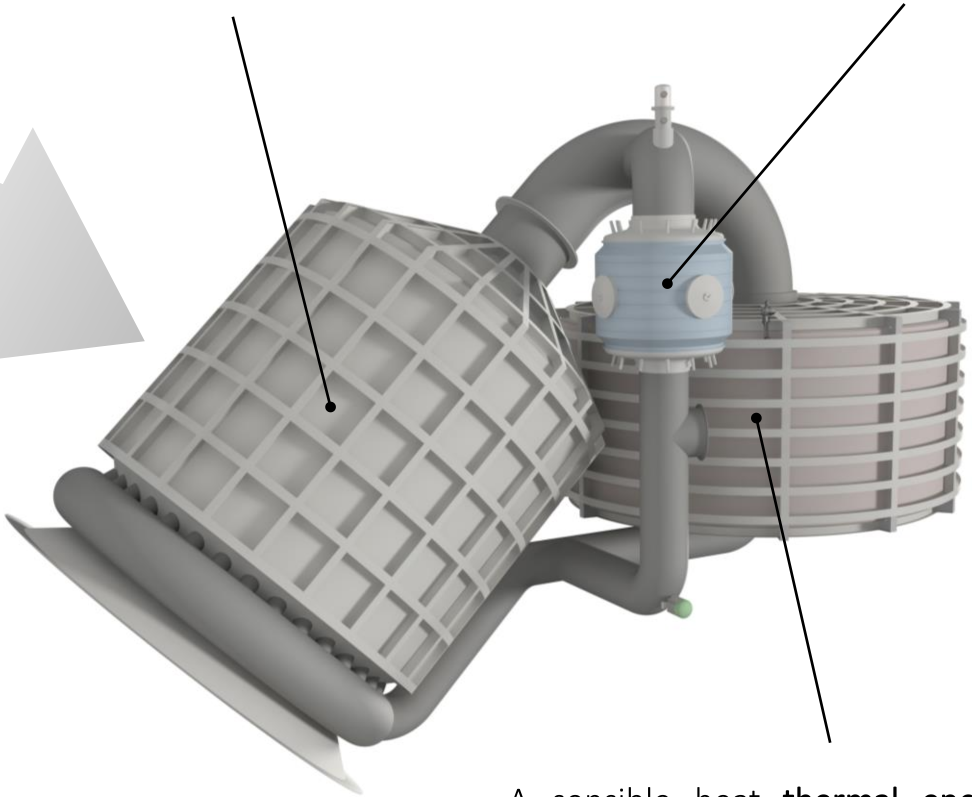
- **Competitive with fossil fuels**
- Up to **50% lower net CO_2** emissions
- Based on industrial reforming technology
- Market ready by 2023

TECHNOLOGY: 3 CORE COMPONENTS

The **solar receiver** efficiently converts the concentrated solar radiation into heat at temperatures up to 1’500°C.

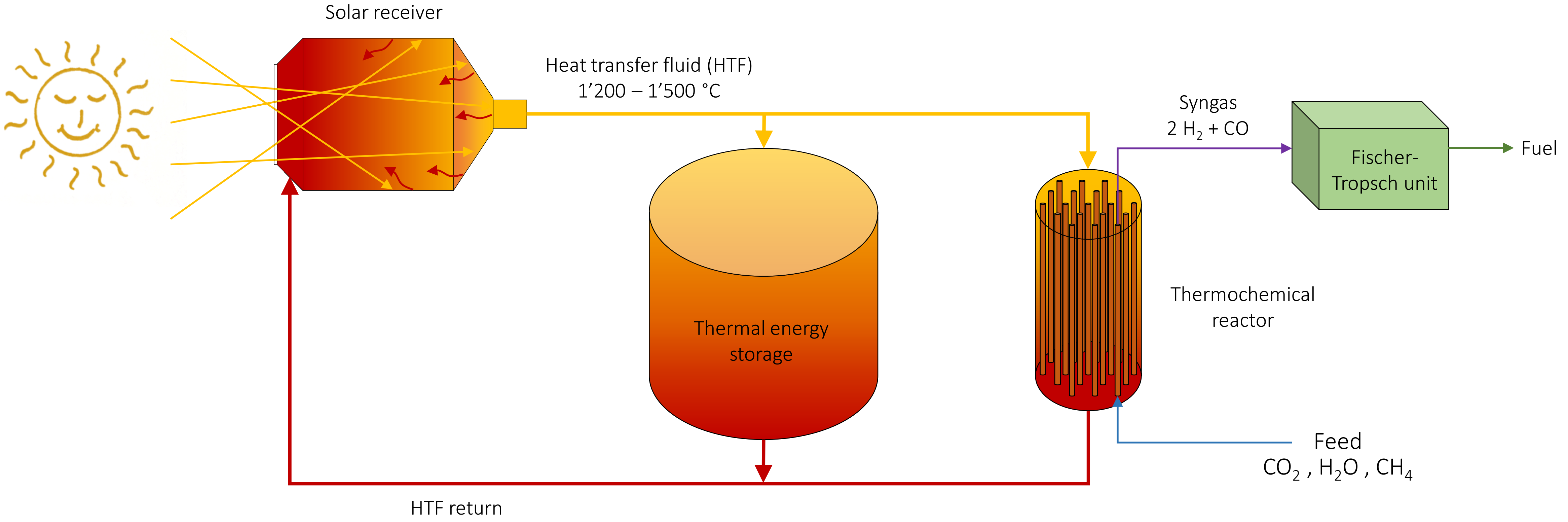
Within the **thermochemical reactor**, the heat delivered by the receiver drives endothermic reactions for syngas production.



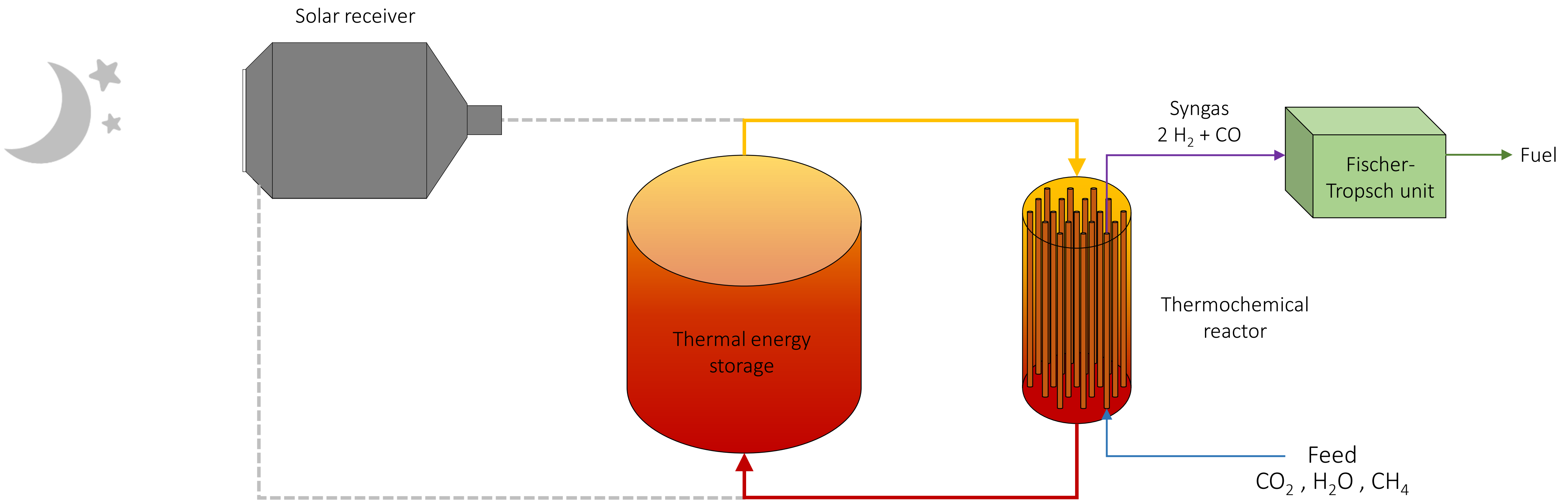


A sensible heat **thermal energy storage** enables continuous 24/7 operation in summer and extended operation in winter.

TECHNOLOGY: FROM SUN TO FUEL



TECHNOLOGY: SEAMLESS THROUGH THE NIGHT



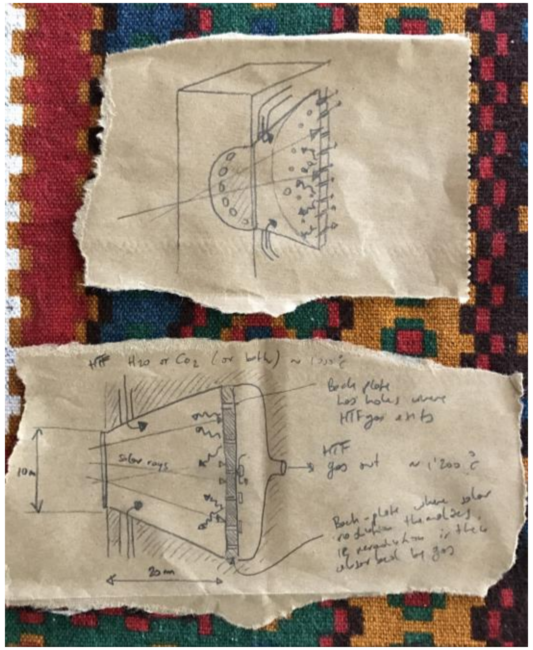
A RECORD-BREAKING PATH TO MARKET

ETH zürich

PREC Professorship of Renewable Energy Carriers

2014

World's first solar kerosene from H_2O and CO_2 in the lab.



2017

We conceived and patented a completely novel high temperature solar receiver concept.

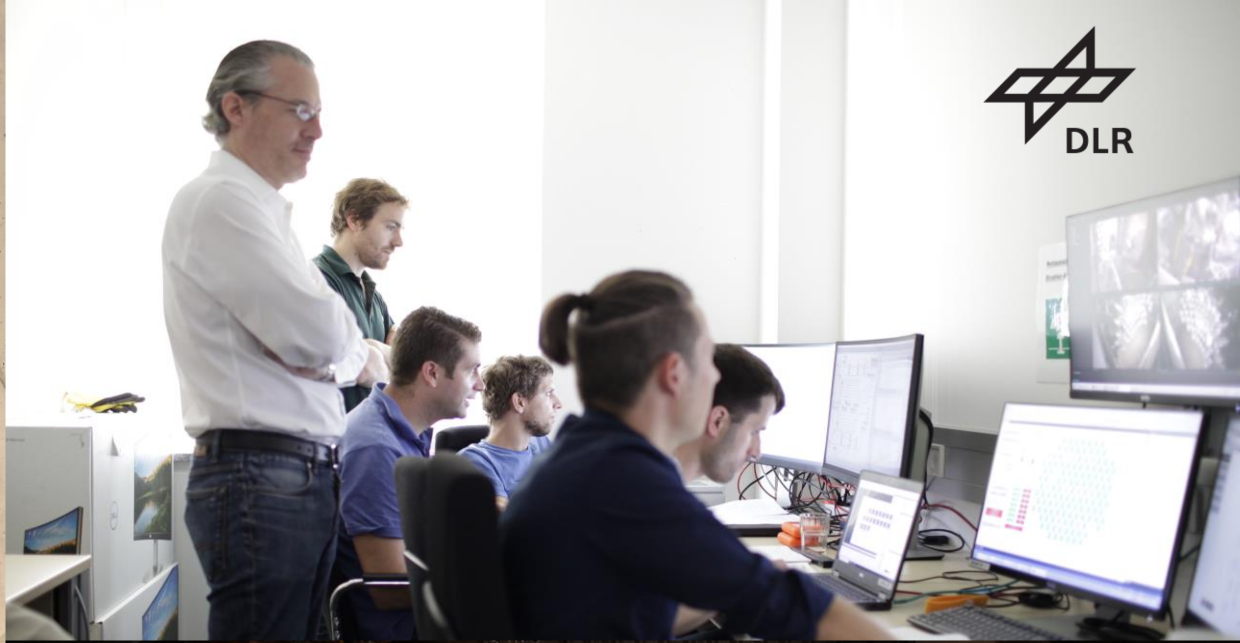
2019

World's first carbon-neutral fuels from air and sunlight.

2019

We built and commissioned a 250kW prototype of our solar receiver to be tested at DLR Synlight – the world's largest artificial sun. We were the first to use the full power of the facility.

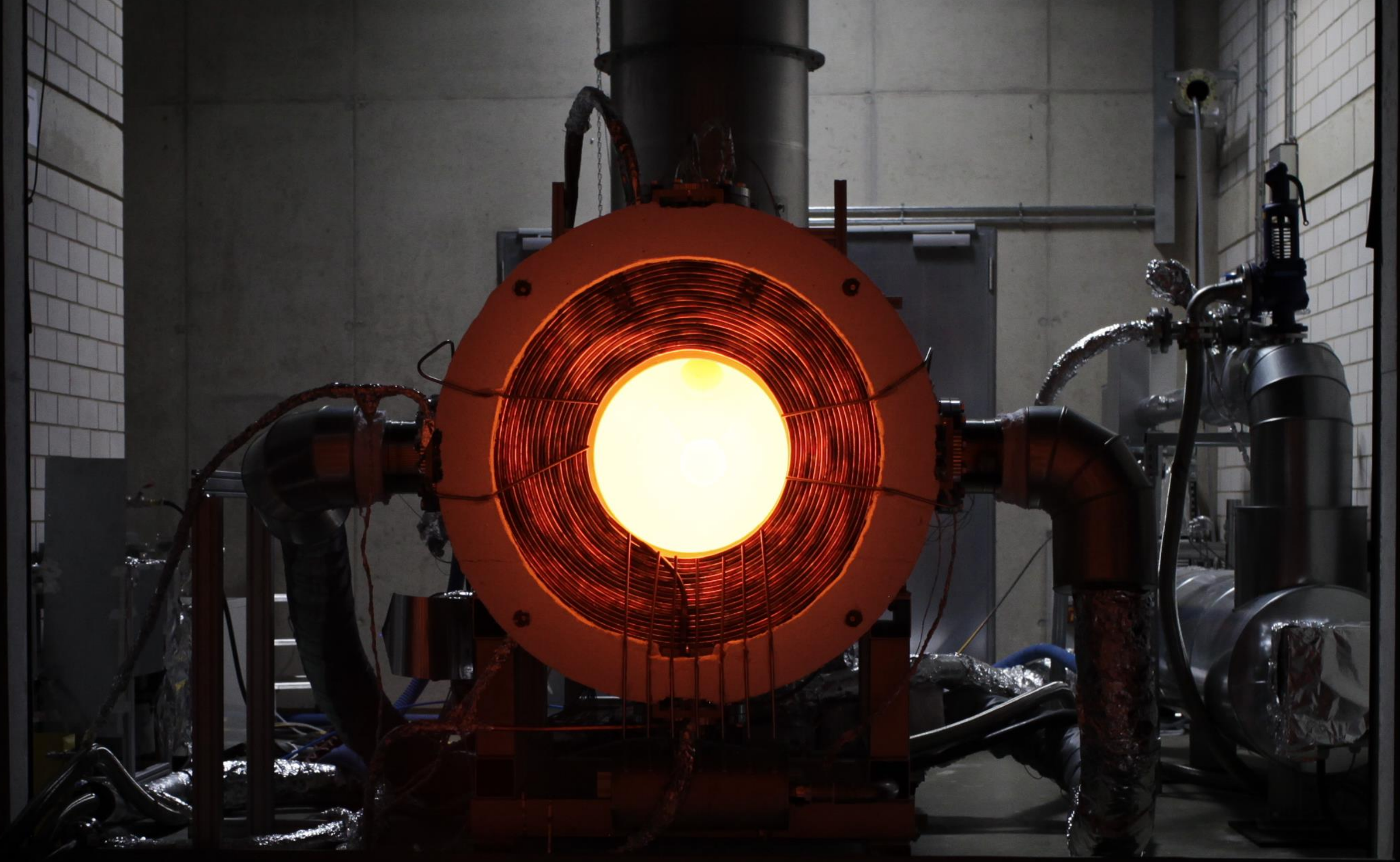
RECEIVER PILOT TESTS



ACHIEVEMENTS 2020 - SOLAR RECEIVER PILOT

250kW receiver pilot successfully tested. Outlet temperatures beyond **1’550°C** reached.

- 350°C more than any receiver ever built.
- 550°C more than any receiver ever built on that scale.



SYNHELION ROADMAP

2023 | Demo phase

Demonstration of solar syngas production at industrial scale

Integration of solar receiver and chemical reactor on solar tower in Jülich, DE

Demo platform with the entire production chain from sun to fuel

2025 | 1st com. plants

Start of commercial phase

First integrated fuels plant:

- Field size: 8’000 m^2
- Capacity: 1’500 t/y
- Upgrading-based

2030 | Capacity ramp-up

Increase of plant size and installation of new plants

Target total capacity: 0.7 Mt/y
Fuel cost target: 1 €/L JET-A1

2040 | Toward net zero

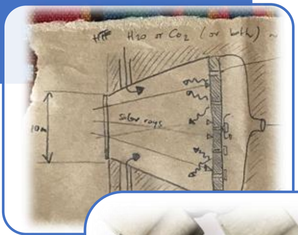
Market entry of carbon-neutral pathways and parallel ramp-up of production capacity

Target total capacity: 40 Mt/y
Fuel cost target: 0.5–1 €/L JET-A1

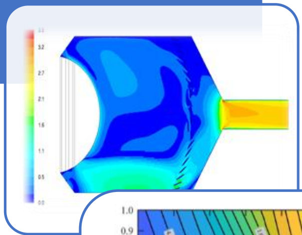
2021: INTEGRATED SYSTEM ON SOLAR TOWER

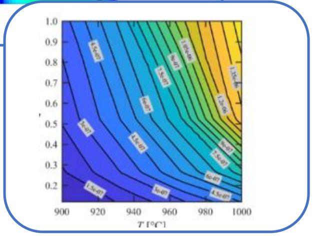
SYSTEM LEVEL ANALYSIS – OUR COCKPIT

Concept



Modeling

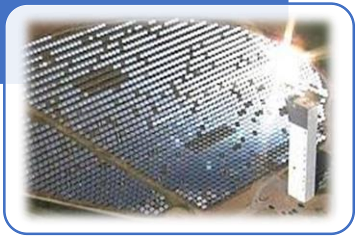


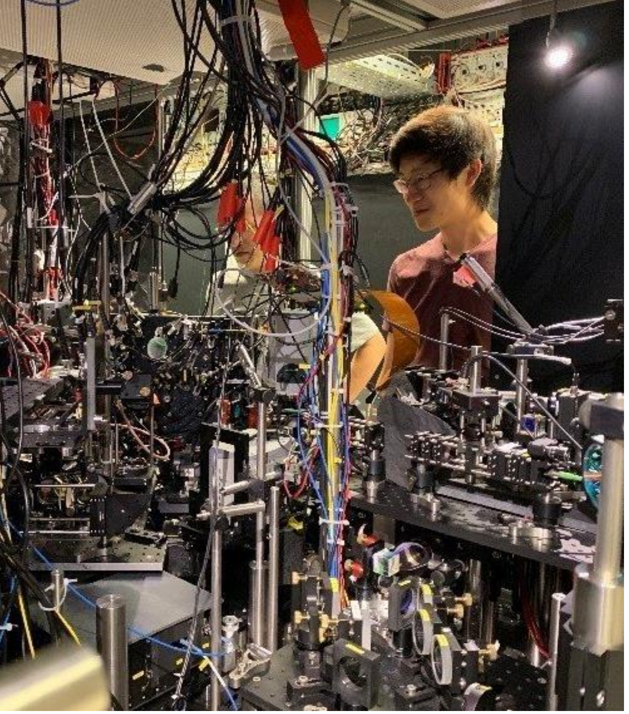


Testing / Validation

Optimization / Scale-up

Integration





KEY RISKS OFTEN OVERLOOKED

- Continuous benchmarking with other technologies / market
- Complexity of approach
- Robustness of technology
- System integration of plant components
- Continuous operation

TEAM AND PARTNERS

eni
CEMEX
wood.
HELIOKON
SWISS
edelweiss
Lufthansa
FLUGHAFEN ZÜRICH

PREC
Professorship of Renewable Energy Carriers
ETH Zurich

Scuola universitaria professionale
della Svizzera italiana
SUPSI

YORK UNIVERSITÉ UNIVERSITY
UF UNIVERSITY of FLORIDA
DLR
institute IMdea
ANSYS CADFEM

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Bundesamt für Energie BFE

Synhelion
solar fuels

THANK YOU!

Follow us on:

Dr. Joe Cresko

Joe Cresko is the Chief Engineer and Strategic Analysis Lead in DOE's Advanced Manufacturing Office (AMO), where he leads AMO's efforts to assess the life cycle and cross-sector impacts of advanced manufacturing technologies. Joe has also served at DOE as an Engineering Sciences Fellow for the Industrial Technologies Program, and a Science & Technology Policy Fellow in the Office of Energy Efficiency & Renewable Energy.

Prior to joining DOE, Joe was the Director of the Emerging Technology Applications Center in Bethlehem, PA, where he helped manufacturers to improve their energy efficiency and environmental footprint through industrial energy efficiency assessments and applied R&D. He has expertise in the application of electrotechnologies for materials processing and manufacturing innovations, including the use of microwave, radio-frequency, induction, UV and electron beam technologies. Joe has performed research, analysis and technology transfer for the aerospace, ceramics, polymer, composites, foundry and food manufacturing industries.

Dr. Ellen Stechel

Ellen B Stechel is Co-Director of ASU LightWorks[Ò]; Professor of Practice in the School of Molecular Sciences; and Senior Sustainability Scientist in the Julie Ann Wrigley Global Futures Laboratory all at Arizona State University. Her career has afforded her opportunities to build and/or coordinate research programs at a national laboratory, industry, a U.S. government agency, and now in higher education at ASU; in both basic and applied research; policy and commercialization of emerging technologies; and in multi-disciplinary, multi-organizational R&D strategy and management.

Dr. Davide Zampini

Dr. Davide Zampini, Ph.D Civil Engineering – Northwestern University (Evanston, IL).
Head of Global Research & Development at CEMEX
Research: materials engineering, cement chemistry, novel binders, construction chemicals, novel construction systems

Mr. Ron Kent

Ron Kent leads the Low Carbon Resource RD&D program at SoCalGas. LCR focuses is on developing renewable and low carbon methane and hydrogen technology pathways. This includes a portfolio of more than 30 projects involving renewable and synthetic methane, hydrogen production, carbon capture, utilization and sequestration, and significantly, two remarkable solar thermochemical projects. Today, Ron will briefly discuss some key take-aways from those projects.

Dr. Peter Pfromm

Dr. Pfromm is a Professor of Chemical Engineering at Washington State University in Pullman, Washington. He has previously served as reviewer and panelist for the National Academies, and served on a DOE BES panel on sustainable ammonia synthesis in 2016. He spent several years in industry early in his career before joining academia with basic and applied research that has been supported by DOE, NSF, USDA, and industrial companies in the pharmaceutical, pulp and paper, and other industries.

Mr. Vikas Tuteja

Vikas is the Chief Operating Officer at Heliogen, the clean energy company focused on eliminating the need for fossil fuels in all sectors of the economy.

He is an operations, finance and strategy professional with over 25 years of experience as an engineer, management consultant, investor, and operator for companies in industries as diverse as telecommunications, industrials, agriculture and cleantech.

Vikas currently manages the development and commercialization of Heliogen's novel concentrating solar technology

Dr. Philipp Furler

Philipp received his PhD in Mechanical Engineering from ETH Zurich and an Executive MBA from the University of Strathclyde. Philipp has more than ten years of experience in high-temperature solar chemistry and reactor engineering and serves as Operating Agent – Solar Chemistry Research for the International Energy Agency's technology program SolarPACES. Prior to joining Synhelion, Philipp co-founded the ETH spin-off company Sunredox, which was acquired by Synhelion in 2018.