Integrating Next Generation Nuclear Reactors with Hydrogen Production

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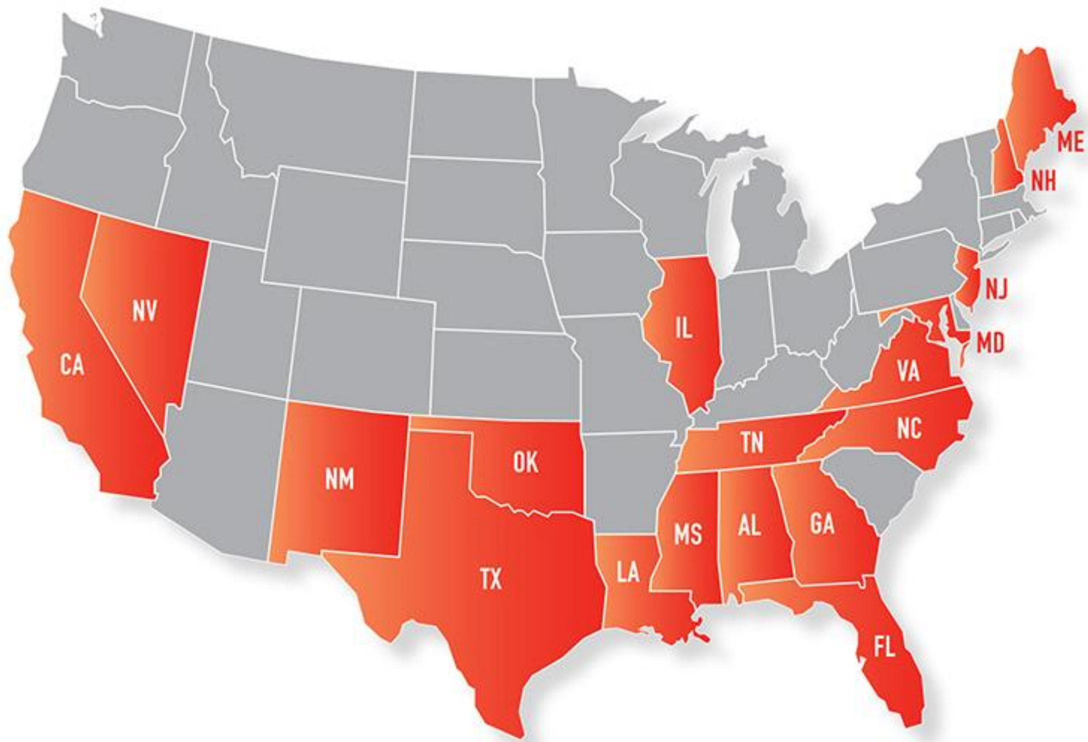
America's Premier Energy Company

Approximately
44,000 MW
of Generating Capacity

Nearly
200,000
Miles of Power lines

More than
80,000
Miles of Natural Gas Pipelines

190 Bcf
of Natural Gas Storage Capacity



Operations in
18 States

11
Electric & Natural Gas Utilities

32,500
Total Employees

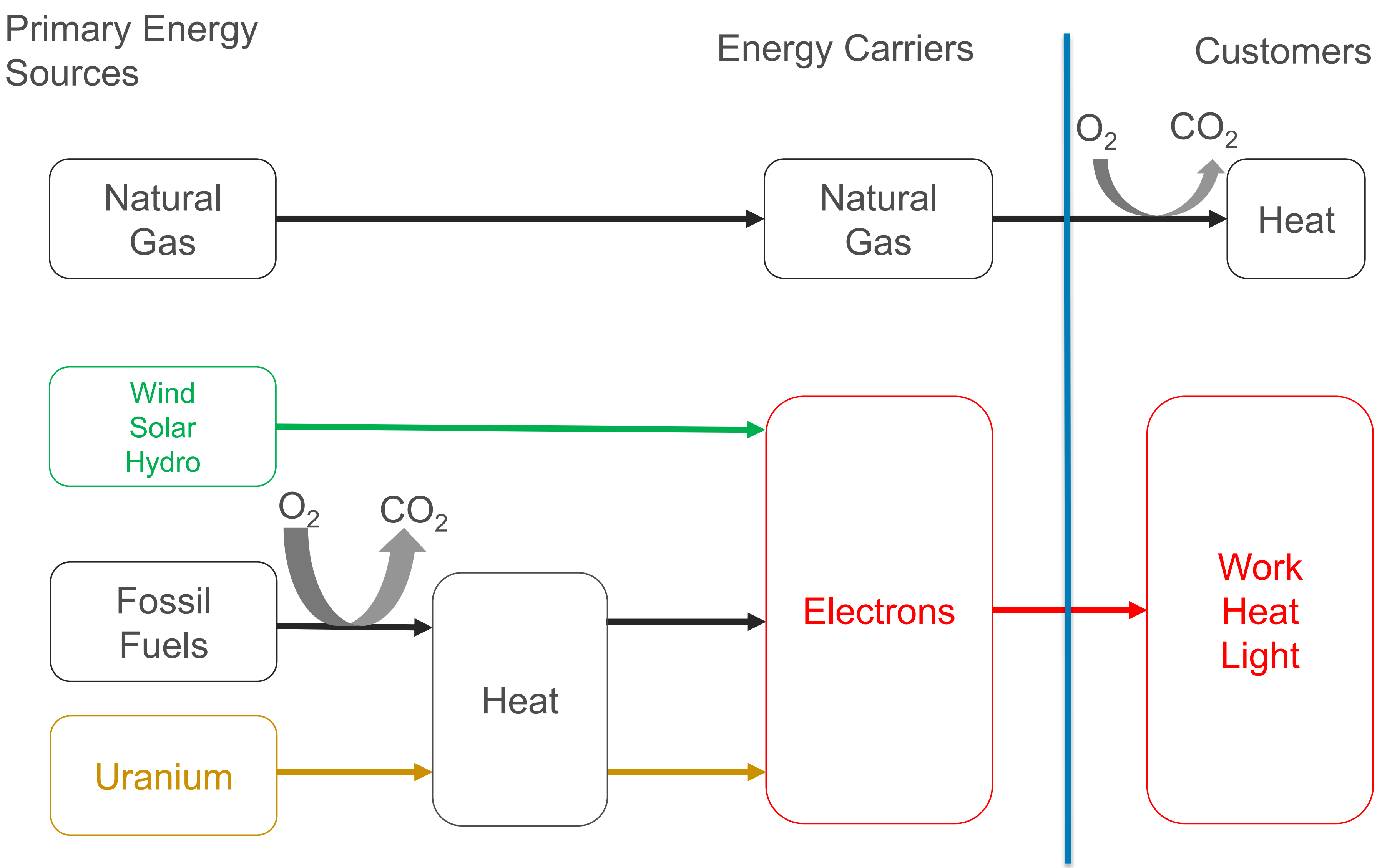
9 Million
Utility Customers

More than
1 Million
Retail Customers

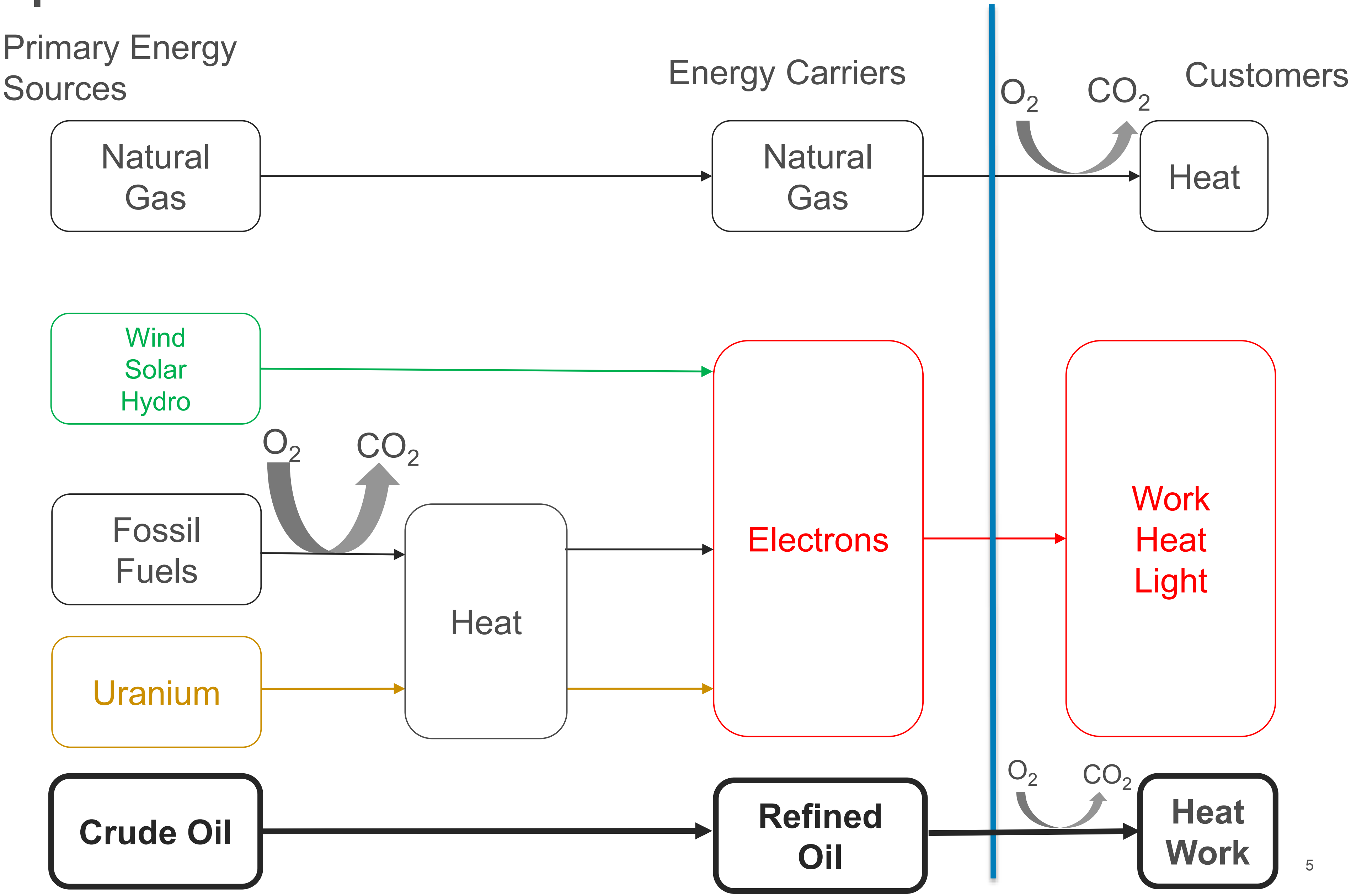
Southern Company Overview

- **Providing clean, safe, reliable and affordable energy for customers and communities**
- **Developing the full portfolio of energy resources**
  - Nuclear
  - 21st century coal
  - Natural gas
  - Renewables (solar, biomass, wind, hydro)
  - Energy efficiency
- **Industry leader in energy innovation**
  - Incubating new products and services at the Energy Innovation Center
  - Engaged in robust, proprietary research and development
  - Company-managed R&D investments totaling approximately $2.1 billion since 1970

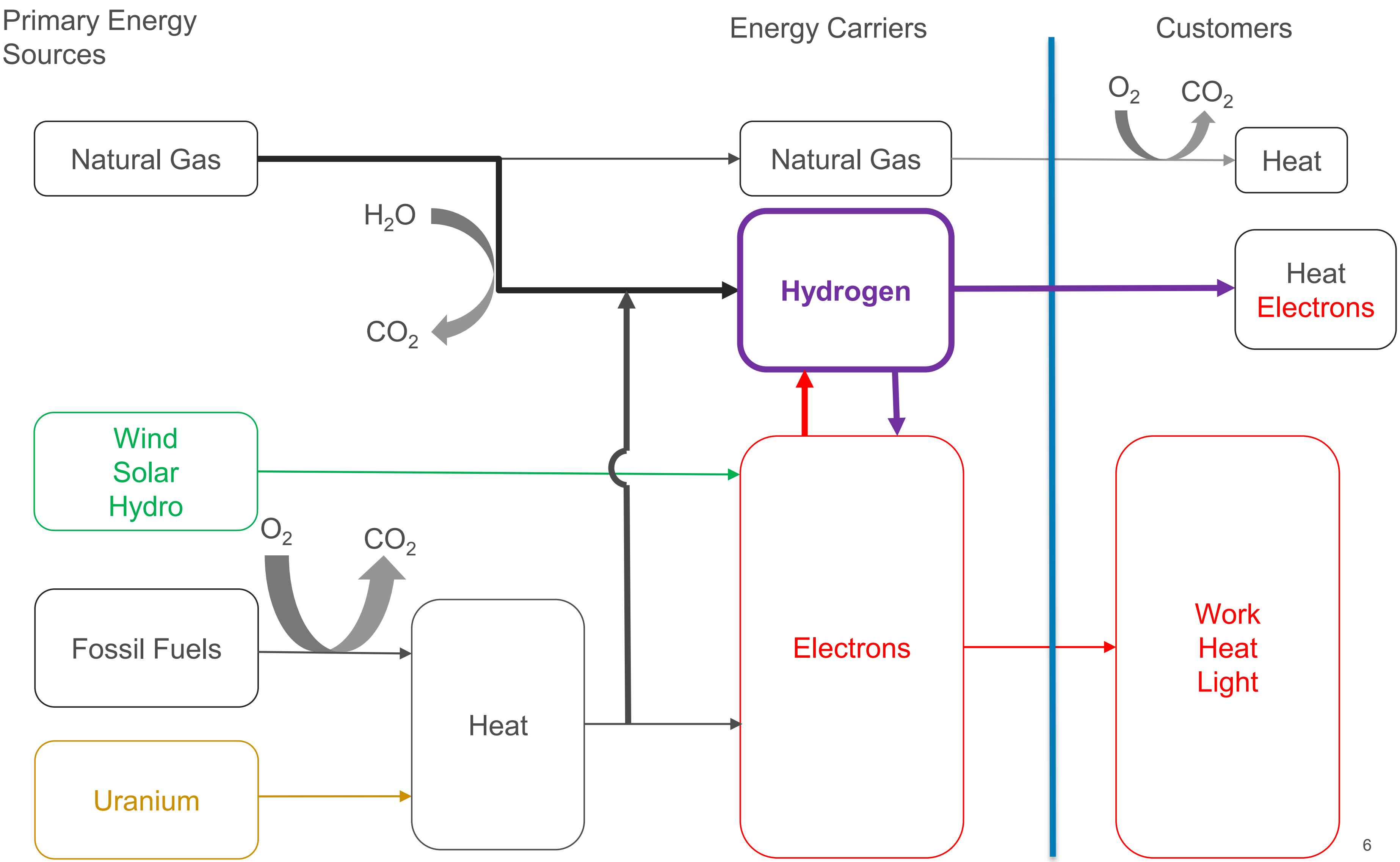
Today, utilities generate and deliver energy carriers in real time.



Today, utilities generally miss a key energy carrier: petroleum.



What if hydrogen becomes an alternate energy carrier for utilities?



Do we have the right energy carrier(s)?

Natural Gas

- Easily stored and transported
- Abundant infrastructure
- Emits CO_2 at point of use

Electrons

- Difficult to store/transport
- Abundant infrastructure
- No emissions at point of use
- Not suitable for some applications

Hydrogen

- Easier to store and transport
- Infrastructure needed
- No emissions at point of use
- Versatile applications

Petroleum

- Easily stored and transported
- Abundant infrastructure
- Emits CO_2 at point of use
- High energy density

Hydrogen is a storable energy carrier which may enable a utility to provide energy with a high capacity factor to existing customers, as well as open up new markets.

5 Ways that Utilities could participate in the Hydrogen Economy

1. Energy storage to achieve high capacity factor and maximize renewables

2. Supplement energy transmission with hydrogen

3. Reduce the carbon footprint and maximize heat value for "green" natural gas

4. Provide hydrogen for dispatchable distributed generation

5. Provide the primary energy source for hydrogen for transportation

Zero-carbon energy options

Renewables

- Poor energy density
- Intermittent
- EROI varies geographically
- Low OpEx

Fossil with CCS

- Good energy density
- Abundant infrastructure
- Dispatchable
- Requires long-term, large-scale CO_2 sequestration
- Variable/high OpEx

Nuclear*

- High energy density
- Dispatchable
- Waste recycle/storage required
- Low OpEx

Nuclear Reactor Design →

Fast	vs	Thermal
Breeder		Burner
Liquid Fuel		Solid Fuel
Thorium		Uranium

COOLANT CHOICE

Salt, Water, Gas, Metal

Advanced Reactor Examples →

ONE

AP1000

Thermal
Burner
Solid Fuel
Water Cooled
Uranium

TWO

TerraPower MCFR

Fast
Breeder
Liquid Fuel
Salt Cooled
Uranium
(Could use Th)

THREE

Terrestrial Energy

Thermal
Burner
Liquid Fuel
Salt Cooled
Uranium
(Could use Th)

FOUR

Flibe Energy

Thermal
Breeder
Liquid Fuel
Salt Cooled
Thorium

FIVE

Transatomic Power

Hybrid
Burner
Liquid Fuel
Salt Cooled
Uranium
(Could use Th)

SIX

General Atomics EM2

Fast
Breeder
Solid Fuel
Gas Cooled
Uranium

SEVEN

Areva HTGR

Thermal
Burner
Solid Fuel
Gas Cooled
Uranium

EIGHT

X-Energy

Thermal
Burner
Solid Fuel
Gas Cooled
Uranium

NINE

TerraPower TWR

Fast
Breeder
Solid Fuel
Metal Cooled
Uranium

TEN

GE Prism

Fast
Breeder
Solid Fuel
Metal Cooled
Uranium

ELEVEN

Toshiba 4S

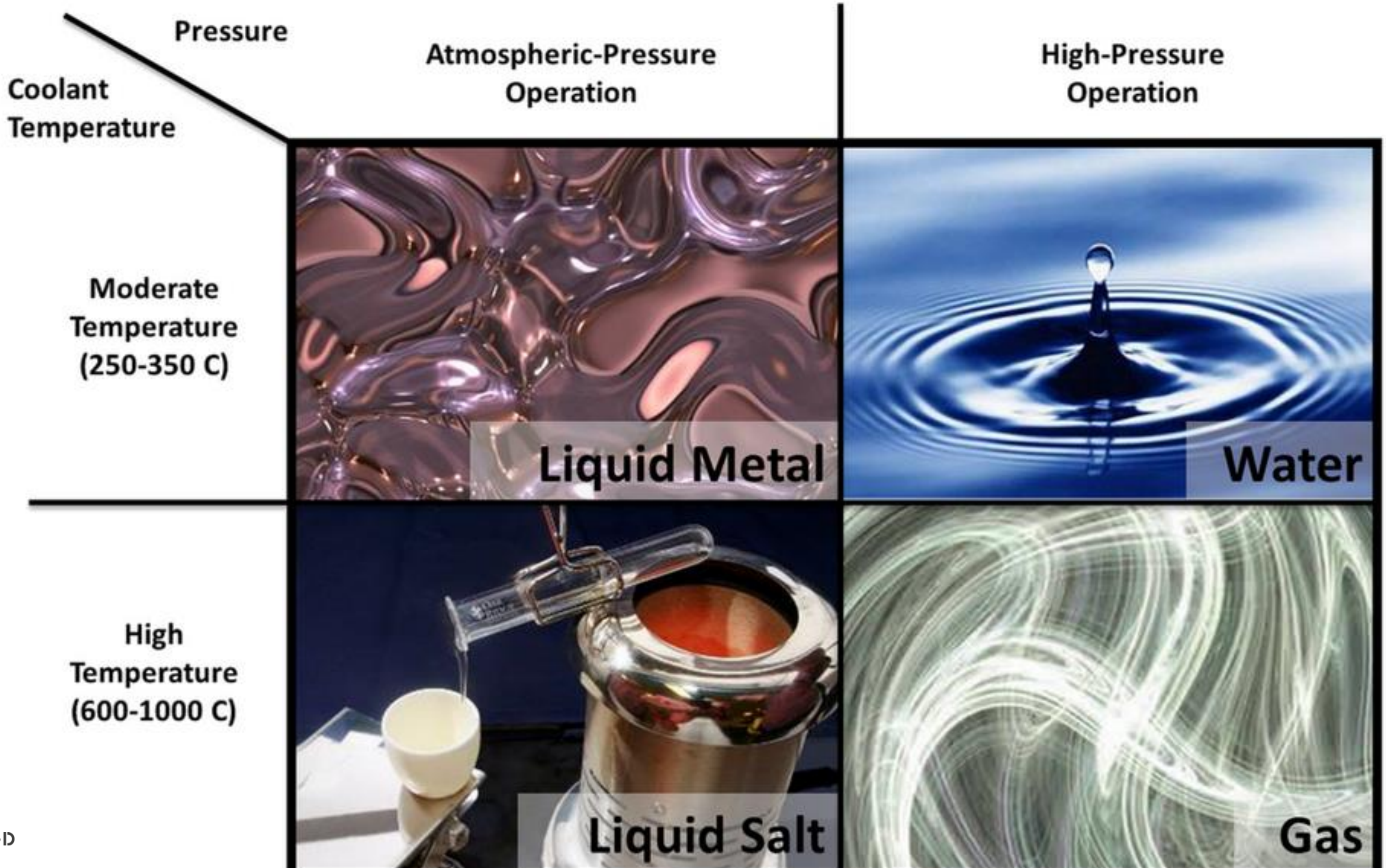
Fast
Breeder
Solid Fuel
Metal Cooled
Uranium

TWELVE

Oklo

Fast
Burner
Solid Fuel
Metal Cooled
Uranium

COOLANT CHOICE

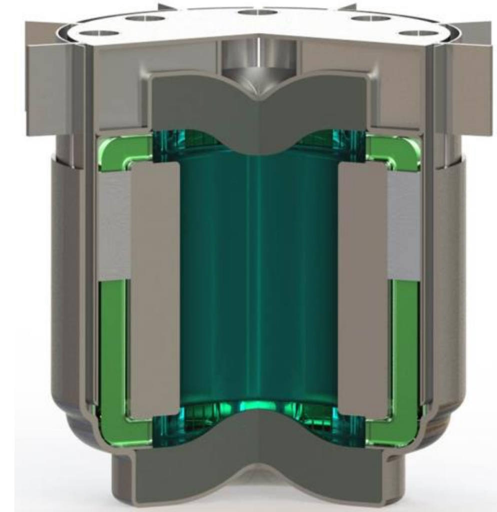


Advanced Reactor Features

	High temperature	Low pressure	Online refueling	Sustainable fuel cycle	High power density	Cooled with natural convection	Complete walkaway safety	Ever been built before
LWR	✗	✗	✗	✗	✗	✗	✗	✓
HTGR	✓	✗	✓	✗	✗	✓	✓	✓
SFR	✗	✓	✗	✓	✓	✓	✓	✓
MCFR	✓	✓	✓	✓	✓	✓	✓	✗

Advanced Nuclear Research

- SCS Selected for $40M DOE Award - Molten Chloride Fast Reactor (MCFR)
- Project will answer key technical questions related to the development of MCFR
  - Demonstrate the relevant phenomena and operations (electrically heated ~2MW)
  - Prepare license application ~30MW Test Reactor
- MCFR meets Southern's goals of Clean, Safe, Reliable, and Affordable energy for the foreseeable future



TerraPower

EPRI

Oak Ridge National Laboratory

Vanderbilt University

R+D

Team Member Roles

- SCS:
  - Project Lead, Project Management
  - Owner/Operator Perspective on Design Decisions
  - Licensing Support
- TerraPower
  - Reactor Design and Systems Engineering
  - Technology Owner
- EPRI
  - Independent Evaluations of Technology
  - Fuel Cycle Analysis
  - Reliability, Accessibility, Maintainability, Inspectability
- Vanderbilt
  - Process Hazard Analysis
  - Pre-PIRT (Phenomena Identification and Ranking Table)

R+D

Molten Salt Reactor Design Challenges

- Corrosion – Redox Potential
- Salt Chemistry – Evolution of Fission Products
- Materials/Coatings Fabrication and Qualification
- Pumps, Heat Exchangers, Valves
- Instrumentation
- Chlorine Isotope Separation
- Licensing
- Access to High Assay LEU
- Vendor Development

R+D

Molten Chloride Fast Reactor Timeline

Integrated Effects Test

- 2016-2019
- 2 MWth

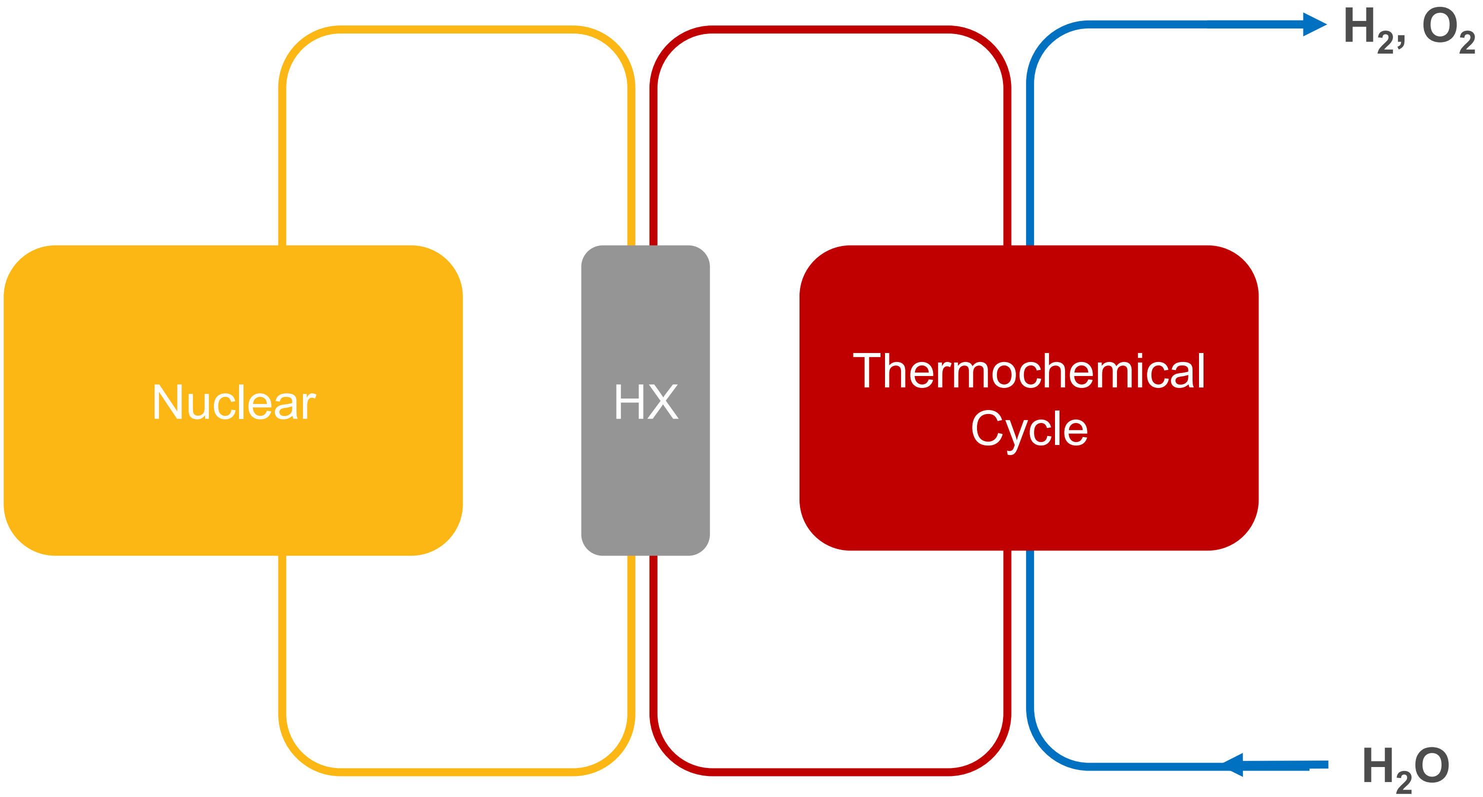
Test Reactor

- 2020-2028
- 30 MWth

Prototype Plant

- 2025-2033
- 2500 MWth

Nuclear-Based Hydrogen Production (NBHP)



ΔT, P, HX design/materials, are critical to successful coupling of nuclear to hydrogen

Types of 2-step Thermochemical Cycles

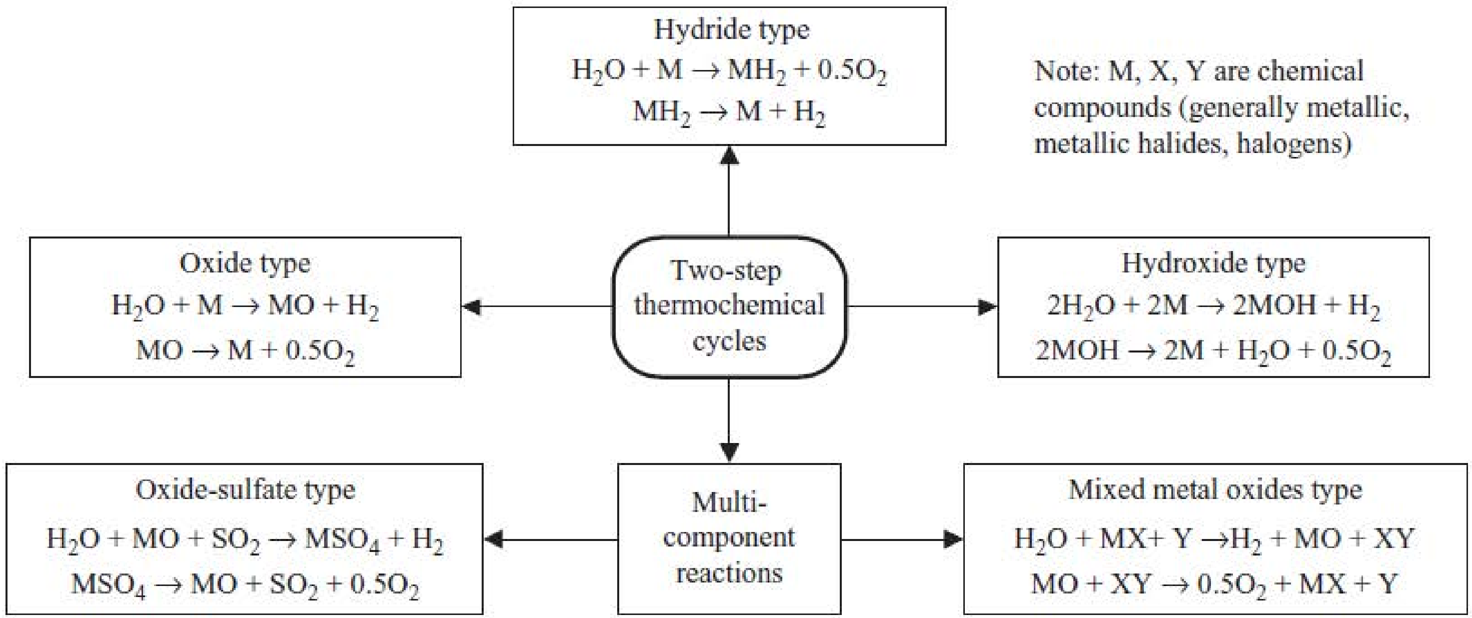


FIG. 4.21 Classification of two-step thermochemical water splitting cycles.

Challenge is most pure thermal, 2-step reactions are >1100 °C.

- Introduce additional steps
- Hybrid thermochemical approach

Figures from: Dincer & Zimfirescu, *Sustainable Hydrogen Production*

Sulfur-iodine vs. hybrid sulfur (HyS)

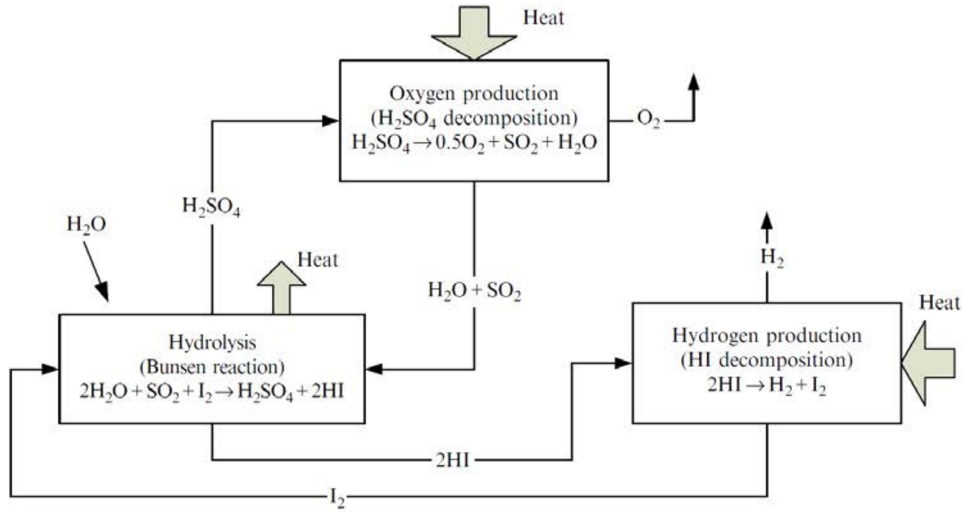
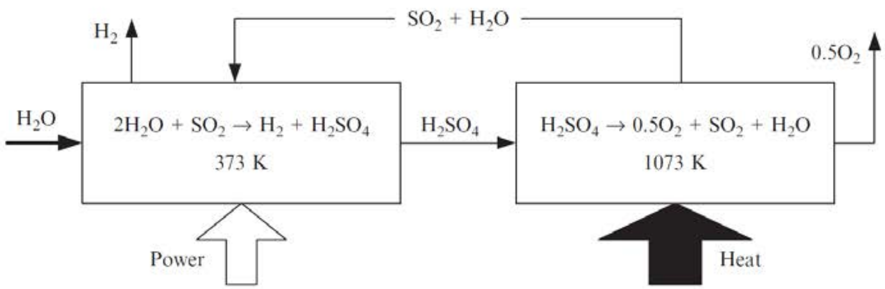


FIG. 4.28 Simplified representation of the thermochemical sulfur-iodine cycle.

HyS process:

- 2 step / 3 unit ops
- Hydrolysis and H_2 production are combined into one electrochemical reaction

FIG. 4.39 Simplified schematic of hybrid sulfur cycle.



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Thermochemical H_2 Research Challenges

- Long-view roadmap
  - "Right" vs. "Right now"
  - Acknowledge changes in energy landscape
  - Nuclear development
- Materials
  - Construction
  - Separations
  - Electrochemical Reactions
  - Heat transfer
- Synergies with other energy objectives
  - Thermal energy storage
  - Thermal reactor materials development
  - Electrochemical reactors

Conclusions

- Hydrogen is a flexible, storable energy carrier that can enable high capacity factor

- Hydrogen can also open up new markets for utilities (DG, CHP, and transportation)

- Gen VI nuclear reactors
- Nuclear-based hydrogen production using thermochemical reactions have high efficiency
  - Many options for optimization

- Research, roadmapping, and collaboration is needed