Integrating Next Generation Nuclear Reactors with Hydrogen Production

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Southern Company Services, Inc,

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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.

Primary Energy Sources

- Natural Gas
- Wind
- Solar
- Hydro
- Fossil Fuels
- Uranium

Energy Carriers

- Natural Gas
- Electrons
- Heat

Customers

- Heat
- Work
- Heat
- Light
- Work

Energy Transformation:

- Crude Oil → Refined Oil → Heat and Work
- Fossil Fuels → Heat and Work
- Wind, Solar, Hydro → Electrons
- Natural Gas → Heat
- Uranium → Heat

Carbon Dioxide (CO₂) and Oxygen (O₂) cycle through the system.
What if hydrogen becomes an alternate energy carrier for utilities?

Primary Energy Sources

- Natural Gas
- Wind
- Solar
- Hydro
- Fossil Fuels

Energy Carriers

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- Hydrogen
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Customers

- Heat
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- Light
**Do we have the right energy carrier(s)?**

<table>
<thead>
<tr>
<th>Energy Carrier</th>
<th>Description</th>
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</table>
| Natural Gas    | - Easily stored and transported  
|                | - Abundant infrastructure  
|                | - Emits CO₂ 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 CO₂ 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 Breeder vs Thermal Burner
Liquid Fuel vs Solid Fuel
Thorium vs Uranium

COOLANT CHOICE
Salt, Water, Gas, Metal
# Advanced Reactor Examples

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<td>Areva HTGR</td>
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<td>TerraPower TWR</td>
<td>GE Prism</td>
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<td>Uranium</td>
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COOLANT CHOICE

Pressure

Coolant Temperature

Atmospheric-Pressure Operation

Moderate Temperature (250-350°C)

Liquid Metal

High-Pressure Operation

High Temperature (600-1000°C)

Liquid Salt

Water

Gas
## Advanced Reactor Features

<table>
<thead>
<tr>
<th></th>
<th>High temperature</th>
<th>Low pressure</th>
<th>Online refueling</th>
<th>Sustainable fuel cycle</th>
<th>High power density</th>
<th>Cooled with natural convection</th>
<th>Complete walkaway safety</th>
<th>Ever been built before</th>
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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
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)
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
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

**Hydride type**

\[ H_2O + M \rightarrow MH_2 + 0.5O_2 \]

\[ MH_2 \rightarrow M + H_2 \]

**Oxide type**

\[ H_2O + M \rightarrow MO + H_2 \]

\[ MO \rightarrow M + 0.5O_2 \]

**Oxide-sulfate type**

\[ H_2O + MO + SO_2 \rightarrow MSO_4 + H_2 \]

\[ MSO_4 \rightarrow MO + SO_2 + 0.5O_2 \]

**Two-step thermochemical cycles**

**Hydroxide type**

\[ 2H_2O + 2M \rightarrow 2MOH + H_2 \]

\[ 2MOH \rightarrow 2M + H_2O + 0.5O_2 \]

**Mixed metal oxides type**

\[ H_2O + MX + Y \rightarrow H_2 + MO + XY \]

\[ MO + XY \rightarrow 0.5O_2 + MX + Y \]

**Multi-component reactions**

*Note: M, X, Y are chemical compounds (generally metallic, metallic halides, halogens)*

**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)

**HyS process:**
- 2 step / 3 unit ops
- Hydrolysis and $\text{H}_2$ production are combined into one electrochemical reaction

Figures from: Dincer & Zimfirescu, *Sustainable Hydrogen Production*
Thermochemical H₂ 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