Nuclear Production of Hydrogen

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Large Scale Production of Hydrogen from Nuclear Power—Fission and Fusion
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Outline

- Hydrogen (H_2) Demand
- Incentives for H_2 Production Using Nuclear Energy
- Compatibility of Nuclear Energy for H_2 Production
- Generation of H_2 from Nuclear Energy
- Conclusions

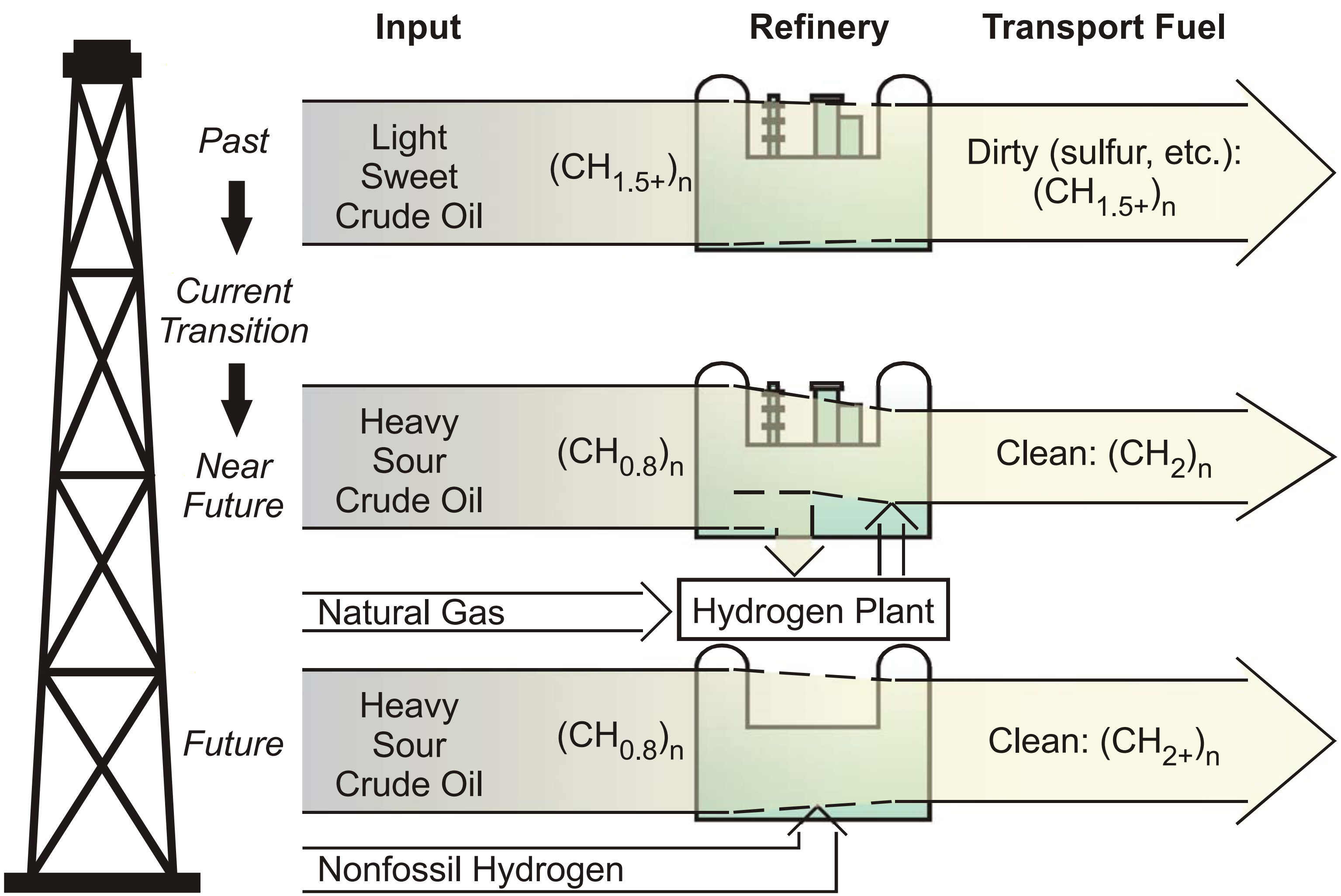
Hydrogen Demand

Current and Future Demand Is Sufficient To Support Nuclear-Generated Hydrogen—If the Technology Can Be Developed

Hydrogen Demand Is Large and Growing Rapidly

- World consumes 50 million tons of H_2/year
  - ~80% intentionally produced; remainder, by-product H_2
  - 200 GW(th) if the H_2 is burned
  - 4 to 10% growth per year
  - Applications: fertilizer, chemical industry, liquid fuels
- Within 10 to 20 years, the energy to produce H_2 in the U.S. may exceed current energy production from nuclear power
- Rapid hydrogen-demand growth to produce clean fuels from lower-grade crude oils

Liquid Fuels Production Is Rapidly Becoming the Major Market for Hydrogen



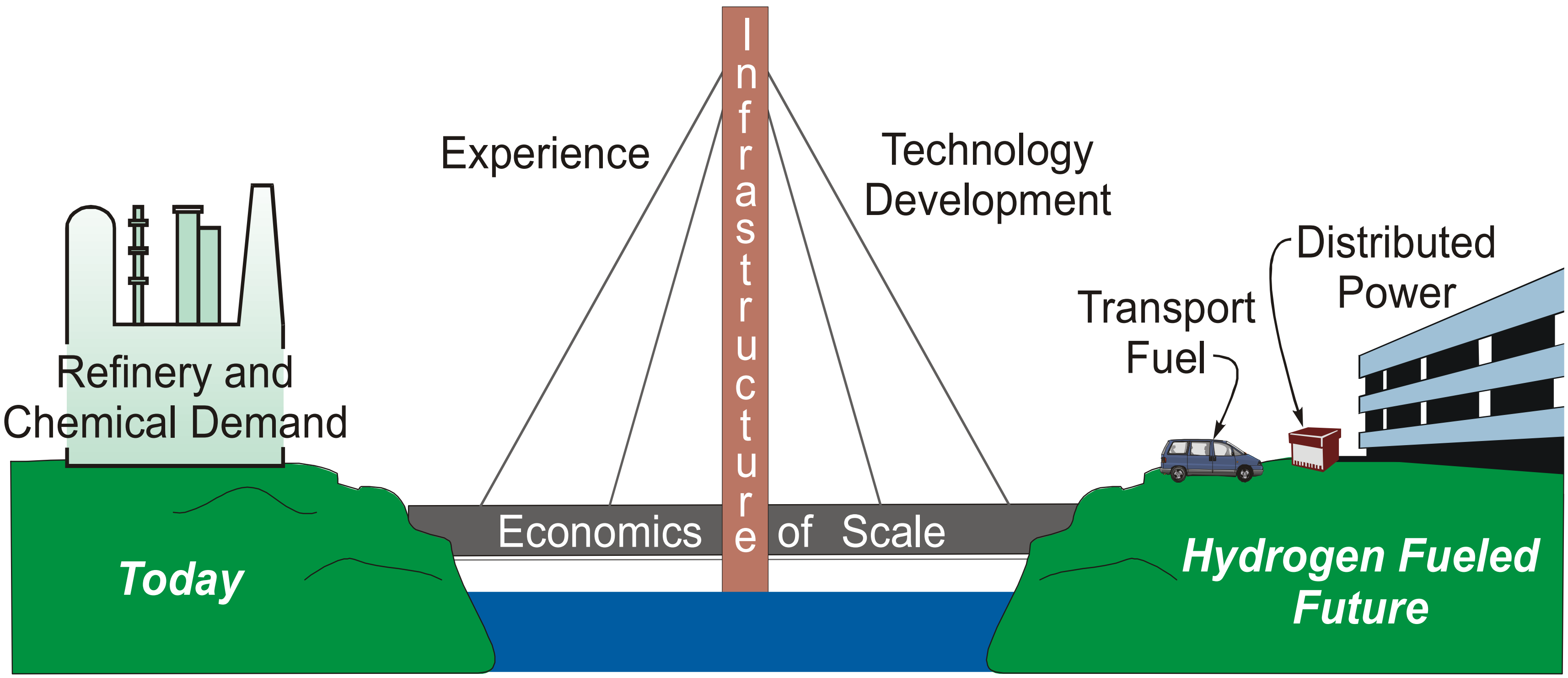
Hydrogen Can Increase Liquid Fuel Yield per Barrel of Oil by ~15%
(Massive potential demand for hydrogen)

- Refineries add H_2 to crude oil to produce clean (gasoline, diesel, jet) fuels
- Variable quantities of H_2 can be added
- If economic nonfossil H_2 were available, the energy value (and volume) of the fuel could be increased by 15% with addition of more H_2 (carbon-saver fuels)
  - Equivalent reduction in crude oil demand
  - Equivalent reduction in carbon dioxide emissions
  - Smoother transition to a future H_2 economy

Refinery Demand for Hydrogen Provides A Transition To A Larger Hydrogen Economy

- Refineries receive H_2 by pipeline
- World-class H_2 production facilities equivalent to 1600 MW(th) reactor
- Experience in handling H_2 on a large scale
- Nuclear facility cost is not a large investment for companies with sales that exceed $100 billion per year

The Growing Hydrogen Demand Creates a Bridge to the Hydrogen Economy—With a Future Hydrogen Energy Demand That May Exceed That for Electricity



Hydrogen Could Exceed Electricity As An Energy Carrier By 2050

- Auto companies and Presidential initiate to develop fuel cells for cars within 10 y
- Technological transitions typically take several decades
  - 40 years from whale oil lamps to electricity
  - 30 years from horses to cars
- If H_2 replaces liquid fuels, H_2 demand may exceed electricity demand
  - Y in energy projections
  - One future: electricity, other future H_2 and electricity
  - No solid basis to predict which future will occur

Incentives for Hydrogen Using Nuclear Energy

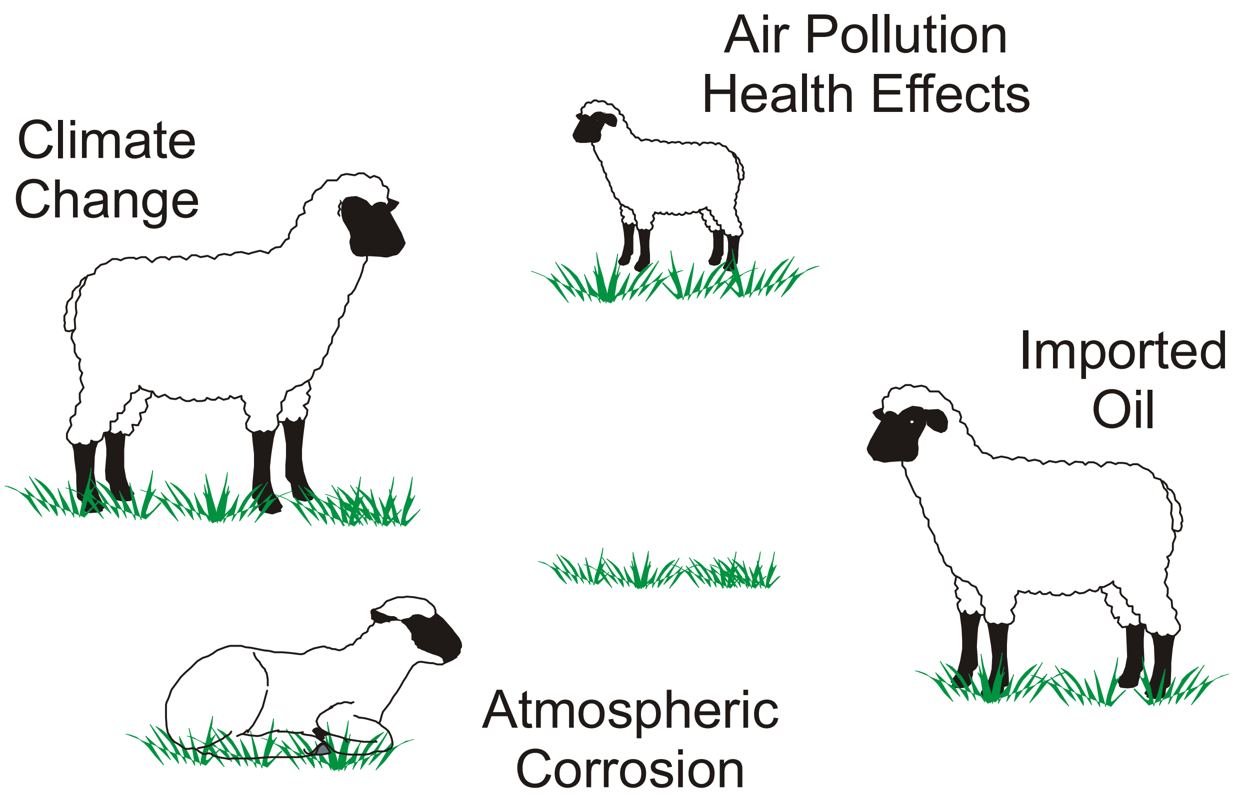
Strategic Incentives Include National Security, Potential Climatic Impacts, and the Problem of the Commons

Oil Dependence Is a National Security Issue

A Hydrogen/Nuclear Economy May Better Internalize Costs

- External costs, defined by economists as the problem of the commons, are costs of a product imposed on third parties (not the producer or consumer)
- External costs of energy (greenhouse impacts, health impacts, building corrosion, national defense, etc.) are large
- Hydrogen minimizes external costs generated by the user (vehicle, building)
- Nuclear externality costs are easier to control

Hydrogen from Nuclear Energy May Reduce the Problem of the Commons (Third-Party Costs)



Compatibility of Nuclear Energy for Hydrogen Production

Intrinsic Characteristics of Different Technologies Determine the Viability of Combining Technologies

Nuclear Facilities Have Remote Siting

- Pipelines are used today to deliver H_2
- Hydrogen plants are often not colocated with H_2 customers
- Pipelines have large capacities compared with nuclear plant output
- Remote siting is acceptable

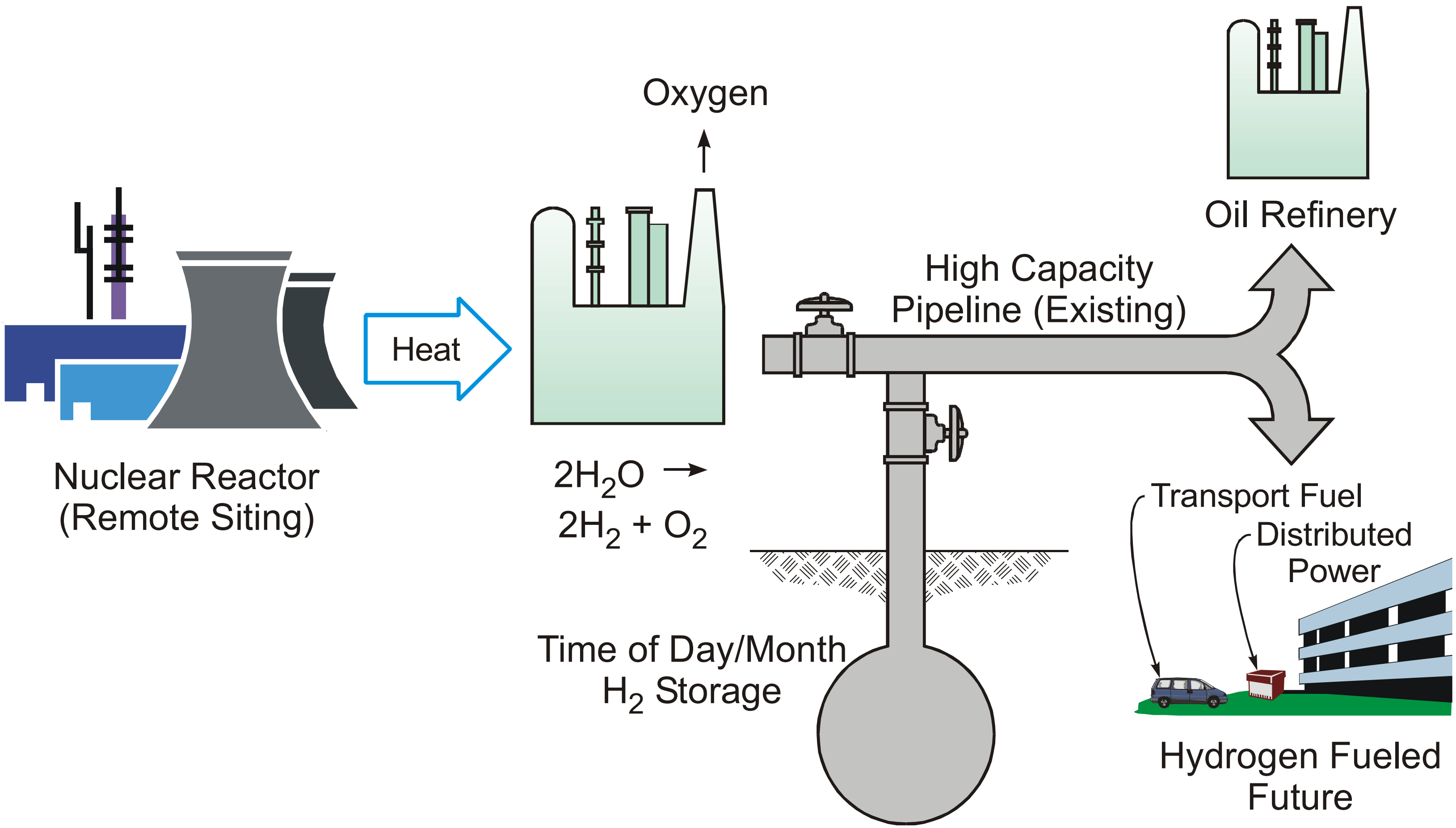
For Hydrogen from Nuclear Energy, the Scale Of the Technologies Must Match

- The economics of nuclear reactors implies energy outputs of 600 to 4500 MW(th)
- New world-class H_2 plants (natural gas fuel) produce 200 million ft^3/day
- Equivalent to 1600 MW(th) reactor (Assuming 50% thermal to H_2 conversion efficiency)
- Comparable sized facilities

Economics Demands Nuclear Reactors Operating at Full Load

- Economic characteristics of nuclear reactors
  - High capital costs
  - Low operating costs
- Hydrogen consumption
  - Current applications: steady demand
  - Future applications: variable demand
- Pipelines allow storage—separate demand from production
  - Pipeline packing (variable pressure)
  - Cavern storage (used for natural gas)

The Intrinsic Characteristics of Nuclear Power Are Compatible with Hydrogen Production
(Remote Siting, Scale of Operations, and Full-Load Operations)



If Fuel Cells Are Successful, Hydrogen Will Exceed Electricity As An Energy Carrier

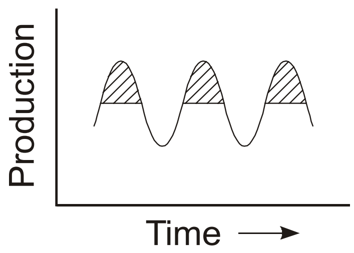
- Energy consumption for transport and electricity are about equal
- Peak electricity demand met by using stored H_2 and fuel cells
- Other H_2 applications exist
  - Heat and electricity fuel cells for high-heat load users
  - Chemical and metallurgical applications
  - Second H_2 era (first era was town gas)
- Combination creates a world with base-load electricity and H_2 production plants
- Base load facilities favorable for nuclear energy with high capital and low operating costs

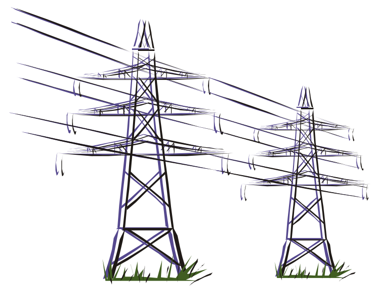
By 2050, Hydrogen Production May Be the Primary Application of Nuclear Energy

(Assuming Fuel Cells Power Vehicles)

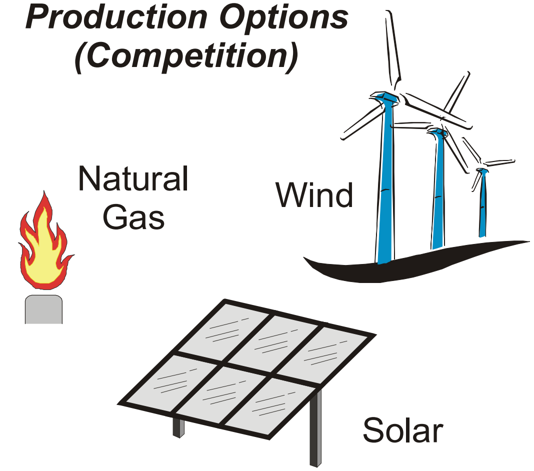
Energy Source	*Production Requirement vs Time (High Capital, Low Operating)*	*Long-Distance Transmission (Remote Siting)*	*Production Options (Competition)*

Electricity





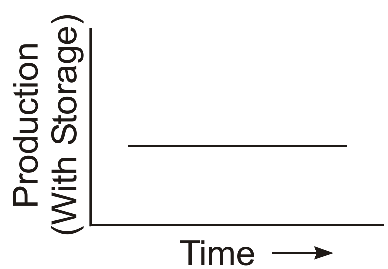
~2 GW

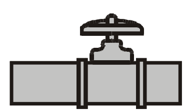


Many

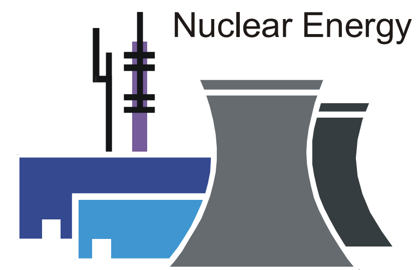
Fuel Cell (Hydrogen to Electricity)

Hydrogen





~25 GW



Few

Generation of Hydrogen from Nuclear Power

Several Technologies Available To Produce Hydrogen Using Nuclear Energy—All Impose Serious Requirements on the Reactor

Characteristics of Current Hydrogen Production Techniques

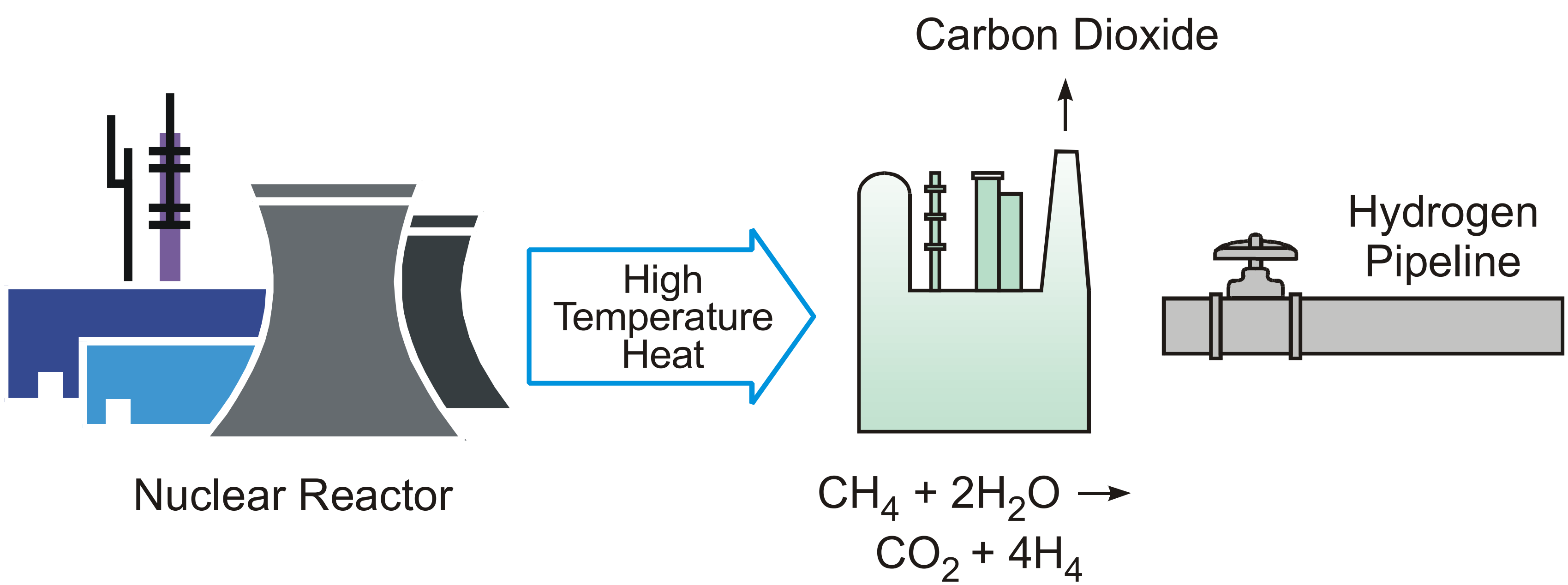
- Most H_2 is made from natural gas
  - Heat + methane (CH_4) + water (H_2O) $\Rightarrow$ hydrogen (H_2) + carbon dioxide (CO_2)
  - Endothermic process with heat input to 900°C
- Water electrolysis is used to produce small quantities of H_2
  - Inefficient: heat to electricity to chemical energy (H_2)
  - Viable where electricity is cheap (night time)

Hydrogen from Steam Reforming

- Heat + methane (CH_4) + water (H_2O) $\Rightarrow$ hydrogen (H_2) + carbon dioxide (CO_2)
- Endothermic process
  - Natural gas option (current practice) uses CH_4 to provide heat (combustion) and reduced H_2
  - Nuclear option (future) replaces some of the natural-gas heat source but not the reduced H_2 from CH_4
- Heat input to 900°C

Nuclear-Assisted Hydrogen Production Uses High Temperature Heat (to 900°C) To Reduce Energy Requirements For Steam Reforming of Natural Gas

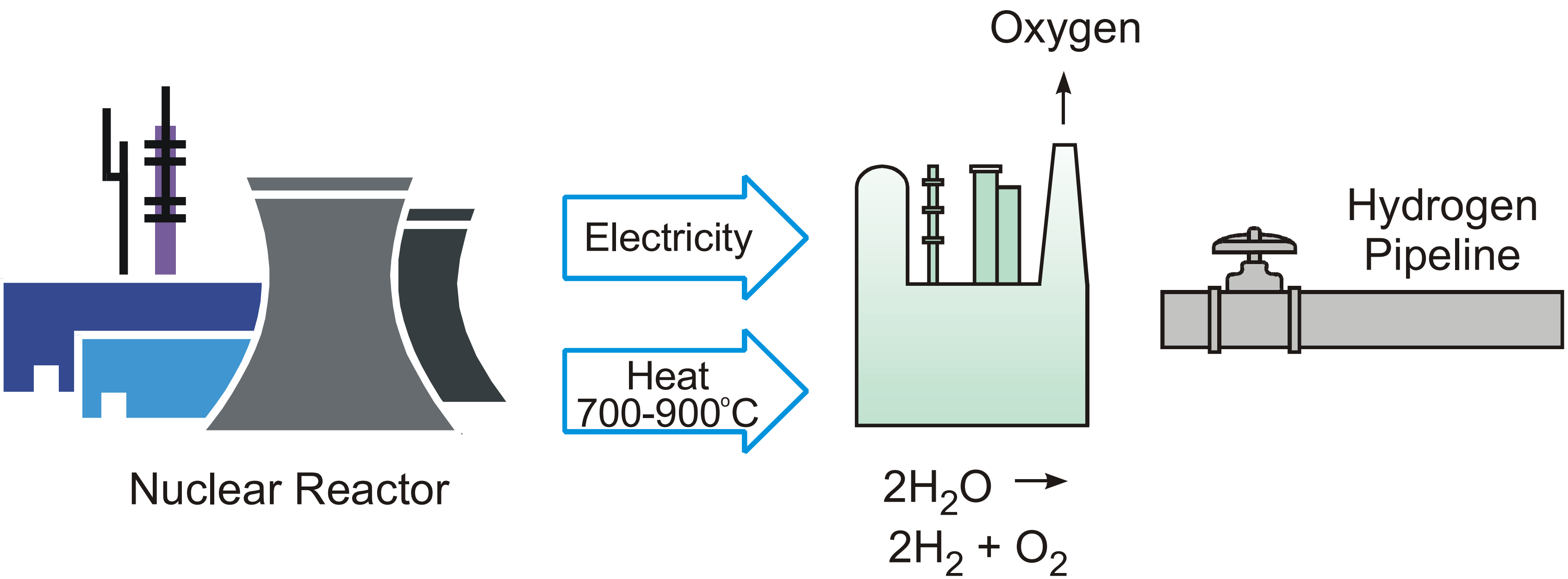
(Development Program in Japan)



Hydrogen from Hot Electrolysis

- Heat + water (H_2O) + electricity $\Rightarrow$ hydrogen (H_2) + oxygen (O_2)
- Heat replaces some of the electric demand
- Heat input at 700 to 900°C

Hydrogen Production Using Hot Electrolysis Requires High-Temperature Heat (700-900°C) and Electricity
(Current Technology Expensive)

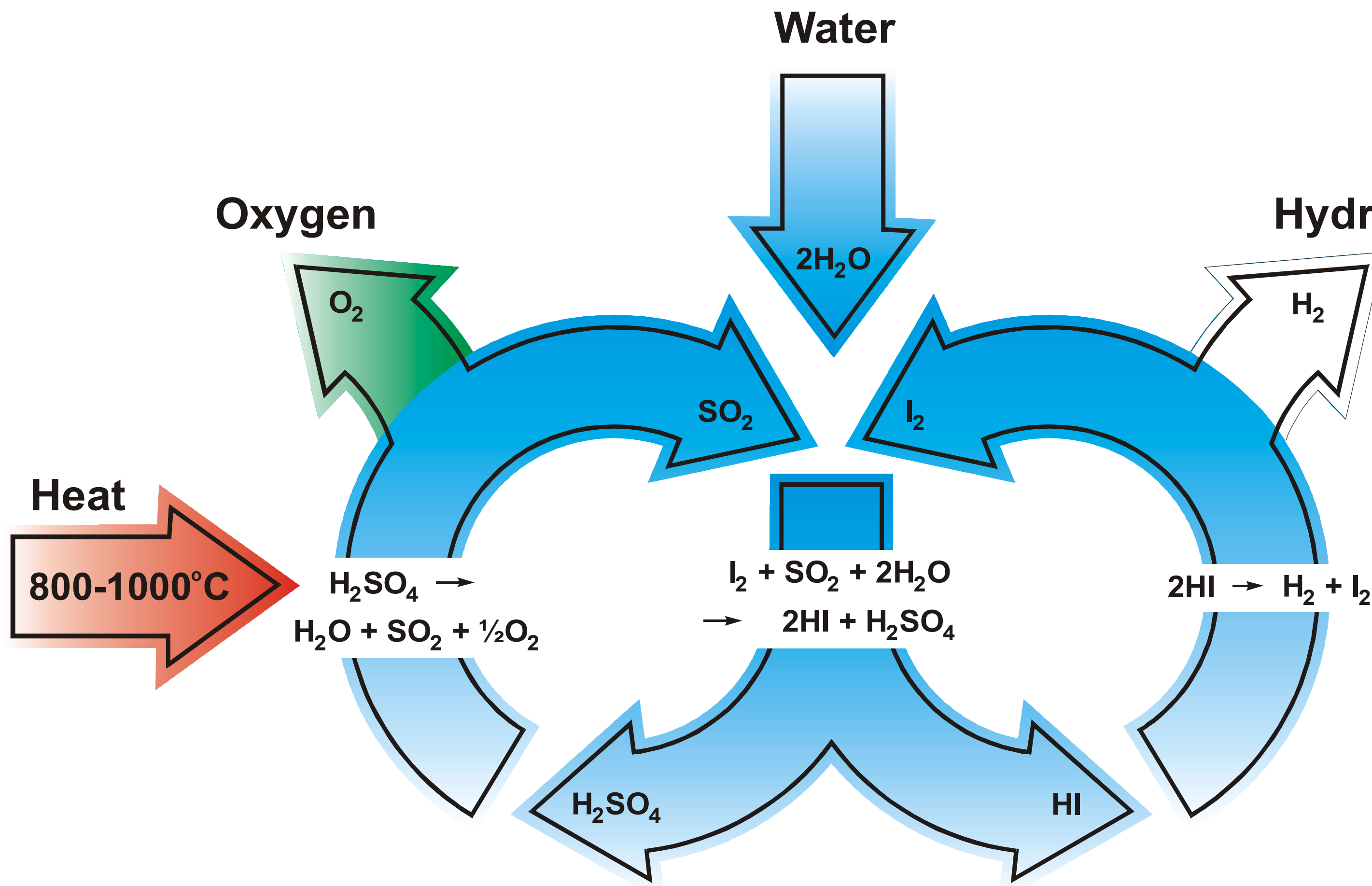


Thermochemical Production of H_2 Is The Leading Technology

- Heat + water ⇒ hydrogen (H_2) + oxygen (O_2)
- Heat input >750°C
- Low pressure
  - Drive chemical reactions
  - Minimize materials requirements
- Lowest potential costs
  - Projected efficiencies of >50%
  - Projected best long-term economics (60% of cold electrolysis)

Thermochemical Processes Convert High-Temperature Heat and Water to H_2 and Oxygen

(Example [leading candidate]: Iodine–Sulfur Process)



High-Temperature, Low-Pressure Heat Required For Nuclear Hydrogen Production

Production Method	Temperature (°C)
Hot Electrolysis	700-900
Assisted Steam Reforming	To 900
Thermochemical	>750

Possible High-Temperature Reactors for Hydrogen Production

- High-Temperature Gas-Cooled Reactor (HTGR)
  - Japan High-Temperature Engineering Test Reactor (HTTR)
- Advanced High-Temperature Reactor
  - Coated-particle fuel similar to HTGR fuel
  - Liquid molten-salt coolant
- Lead-Cooled Fast Reactor

Conclusions

- The demand for H_2 is large and growing
- The intrinsic characteristics of nuclear energy and H_2 production match
  - Scale of operations
  - Demand versus time (better than electricity)
  - Siting
- H_2 production requires high temperatures
- Several nuclear reactor concepts have to potential to match H_2 requirements
- Major R&D is required