Replacing Liquid Fossil Fuels with Liquid Biofuels from Large-Scale Nuclear Biorefineries

Integrating Nuclear, Electricity, Heat Storage, Hydrogen and Biofuels

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Replacing Liquid Fossil Fuels with Liquid Biofuels from Large-Scale Nuclear Biorefineries

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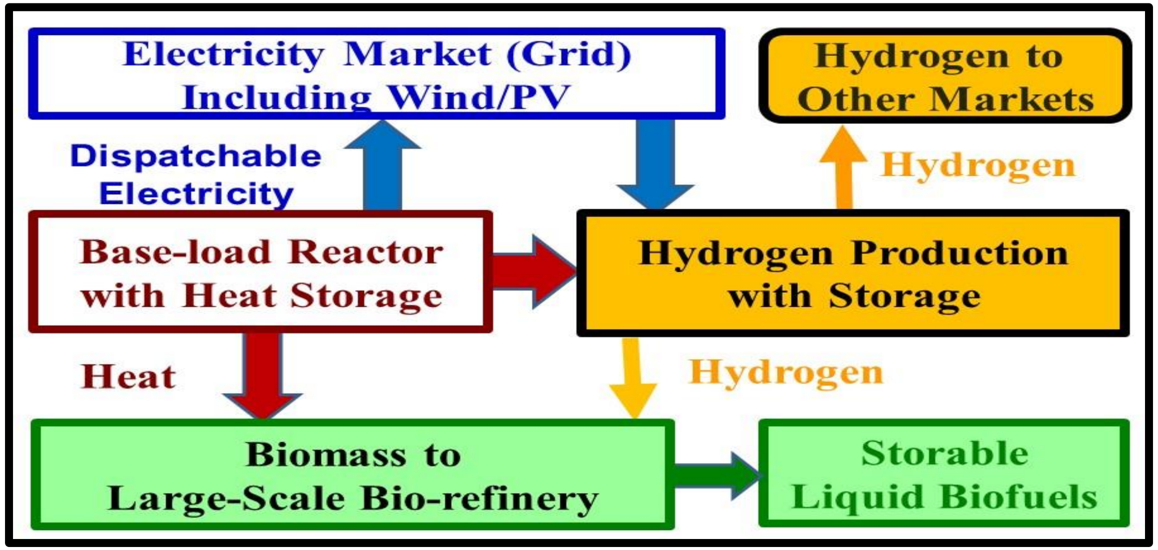
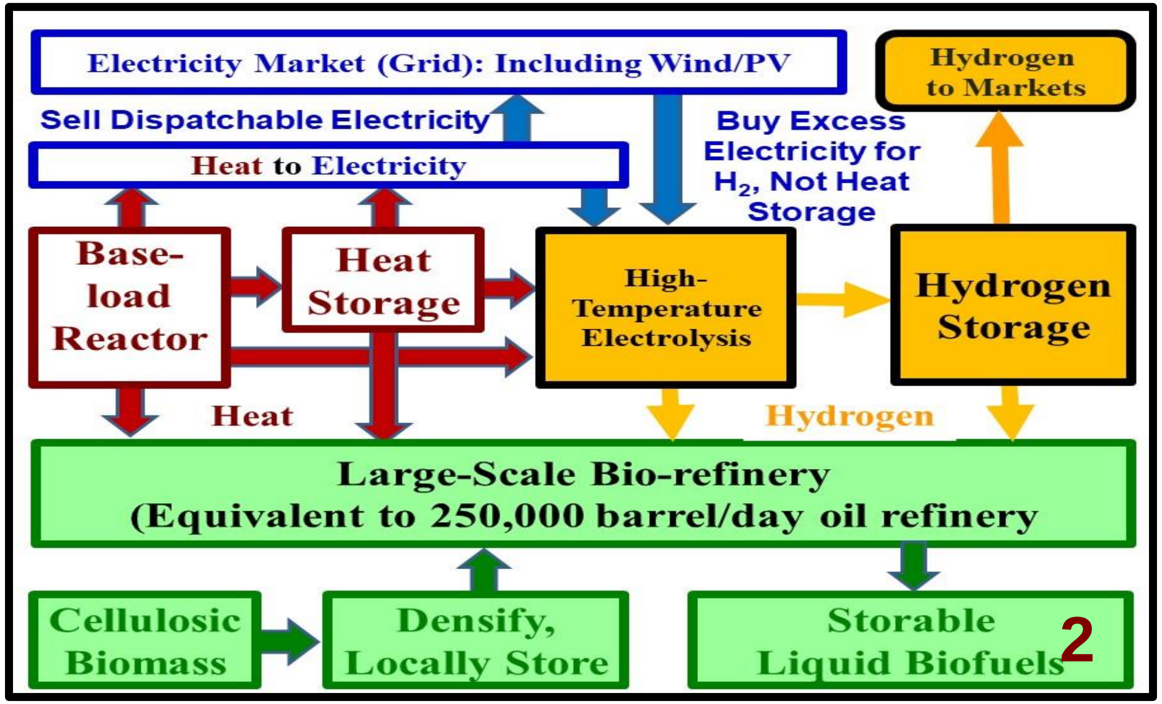
Fossil fuels enabled modern civilization and moved billions of people to the middle class because of their reasonable cost, transportability and storeability. We describe a low-carbon nuclear liquid-biofuels system that provides dispatchable electricity, hydrogen (H_2) and liquid biofuels. Low-carbon systems (nuclear, wind, solar, hydrogen and biorefineries) are capital intensive; thus, they must operate near full capacity to minimize costs. High-capacity factors for these systems are made possible by low-cost heat, H_2, densified biomass and biofuels storage. The reactor, heat storage, H_2 production and biorefinery are co-located because of heat integration.

A nuclear system with gigawatt day-to-week heat storage provides dispatchable electricity, heat for H_2 production and heat to the biorefinery. Heat and electricity with high-temperature electrolysis provide H_2 for bio-refining and other markets. Cellulosic biomass is converted into a high-density storable solid intermediate product near the farm for latter long-distance transport to large-scale biorefineries where low-carbon nuclear heat and hydrogen inputs produce high-quality liquid biofuels. Heat and H_2 inputs can nearly double liquid biofuels production per unit of biomass. The large scale provides economics-of-scale and enables more sophisticated processing producing higher biofuels yields and fewer low-value secondary products. The technologies at the lowest state of commercial readiness are local densification of biomass and large-scale heat storage



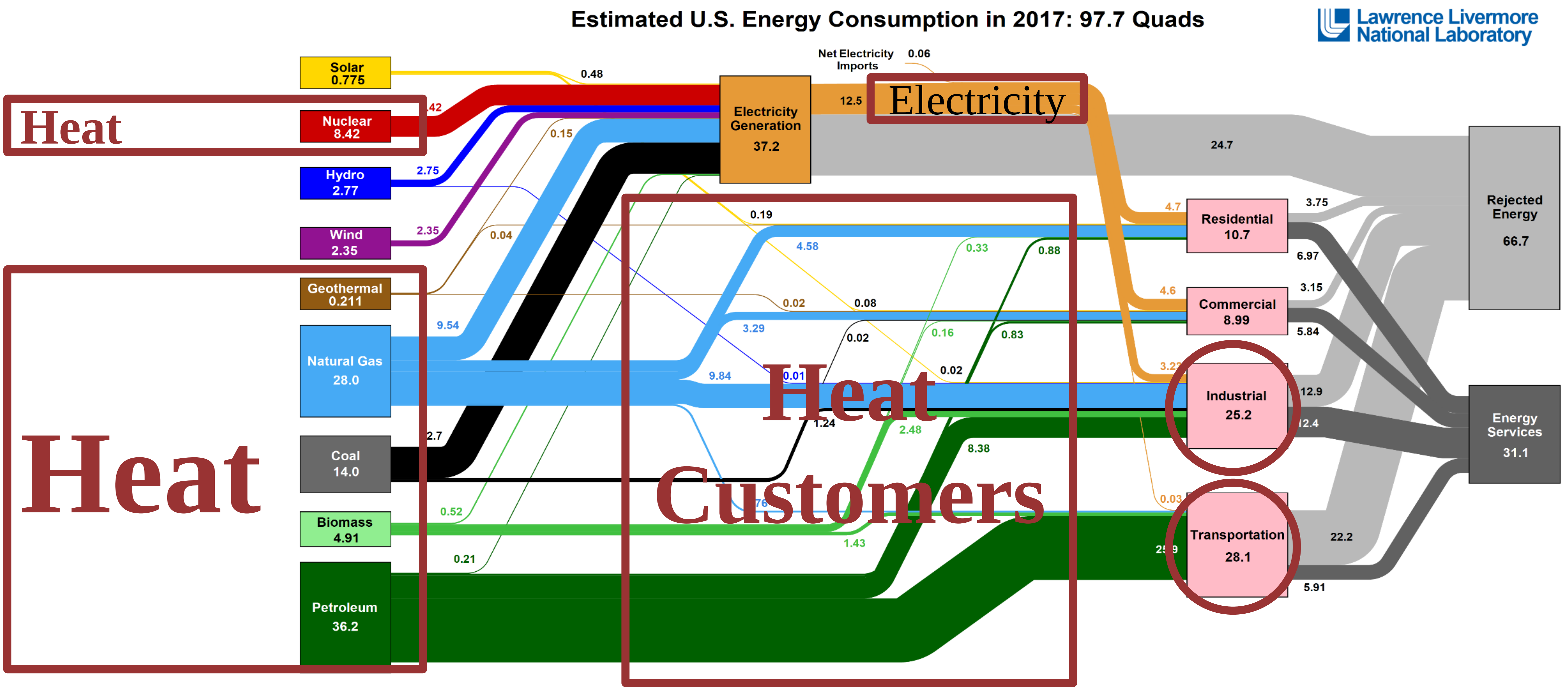


Outline

- The Low-Carbon Electricity/Liquid Fuels Challenge
- Large-scale Nuclear, Electric, Hydrogen, Biofuels System Design
- Low-Carbon Large-Scale Biofuels with Heat and Hydrogen Inputs
- Nuclear System with Heat Storage for Variable Electricity and Heat
- Low-Carbon Hydrogen Production
- Systems Integration: Critical Challenges

The Low-Carbon Electricity / Liquid-Fuels Challenge

Most Energy Is Generated and Used as Heat



Industry and Transportation Use Most Energy

Heat Generating Technologies Produce Cheap Heat

Low-Carbon Low-Cost Heat: Nuclear and Fossil with Carbon Capture and Sequestration

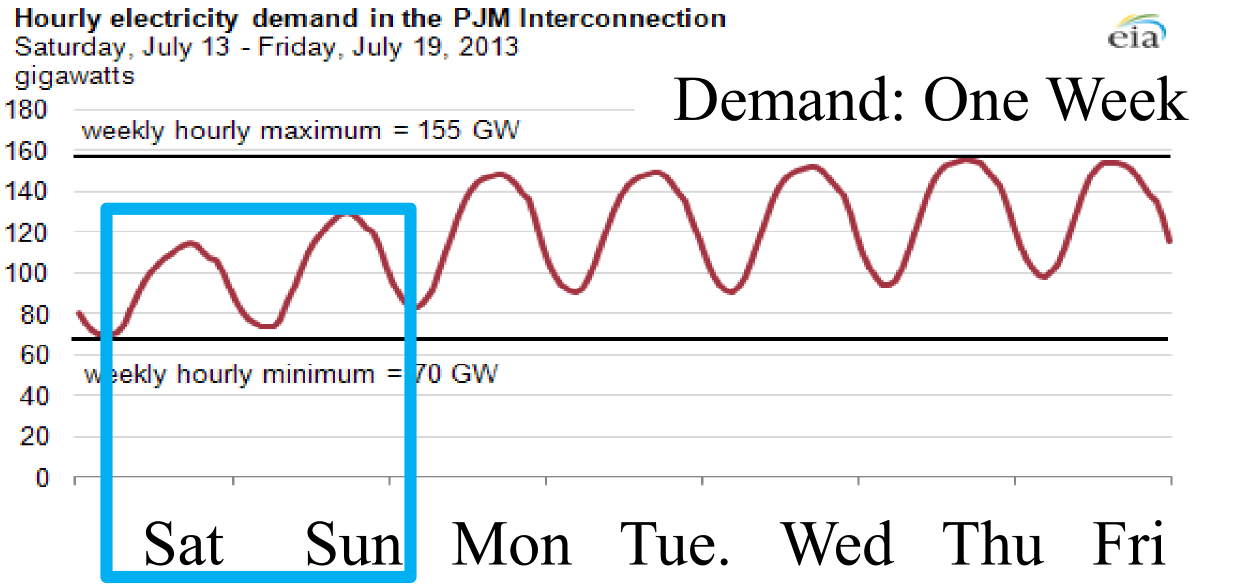
- Several units of heat to create one unit of electricity (Carnot)
- Delivered electricity costs about double production costs
- Wind / solar result in expensive heat
- Heat generating technologies produce cheap heat

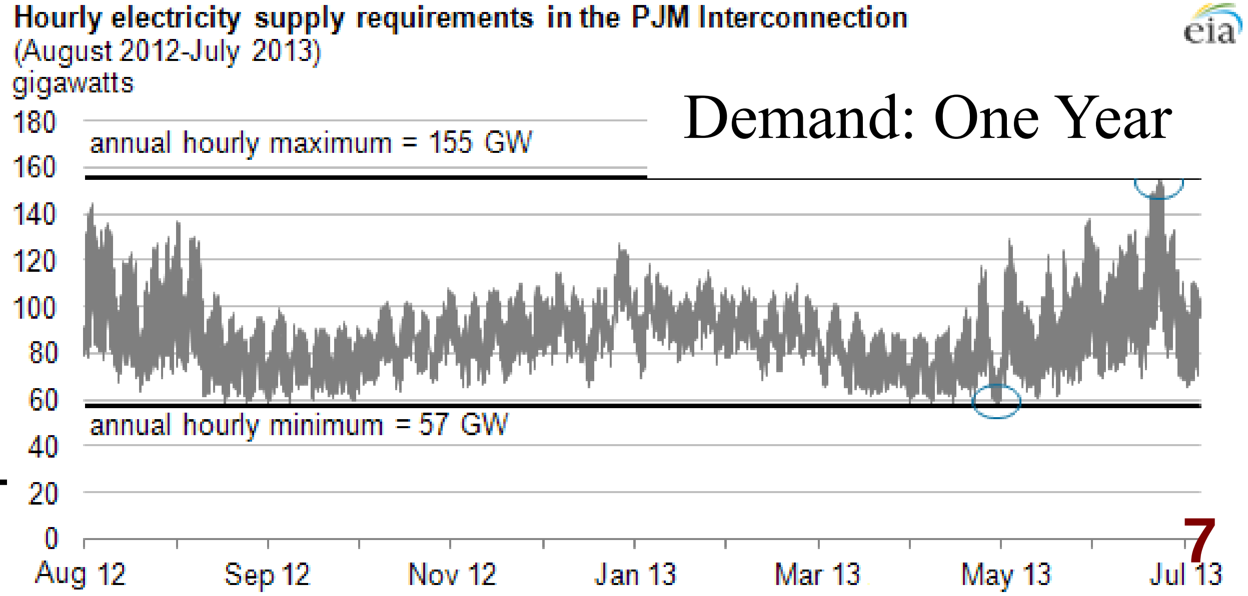
Technology	LCOE: $/MWh(e)	LCOH: $/MWh(t)	
Solar PV: Rooftop Home	187–319	187-319	Add Delivery Costs
Solar PV: Crystal, Utility	46–53	46-53	
Solar PV: Thin Film Utility	43–48	43-48	
Solar Thermal w Storage	98–181	33-60	
Wind	30–60	30-60	
Natural Gas Peaking	156–210	20-40	
NG Combined Cycle	42–78	20-40	
Nuclear	**112–183**	**37-61**	

U.S. Levelized Cost of Electricity (LCOE): (Lazard 2017) and Levelized Cost of Heat (LCOH)

Low-Carbon Electricity Systems Need Storage (Hourly, Daily, Weekly and Seasonal) to Match Production with Demand

- Low-carbon technologies have high capital costs and low operating costs
  - Nuclear
  - Solar
  - Wind
  - Fossil fuels with CCS
- Must operate near full capacity to minimize costs
- Maximum outputs do not match electricity demand



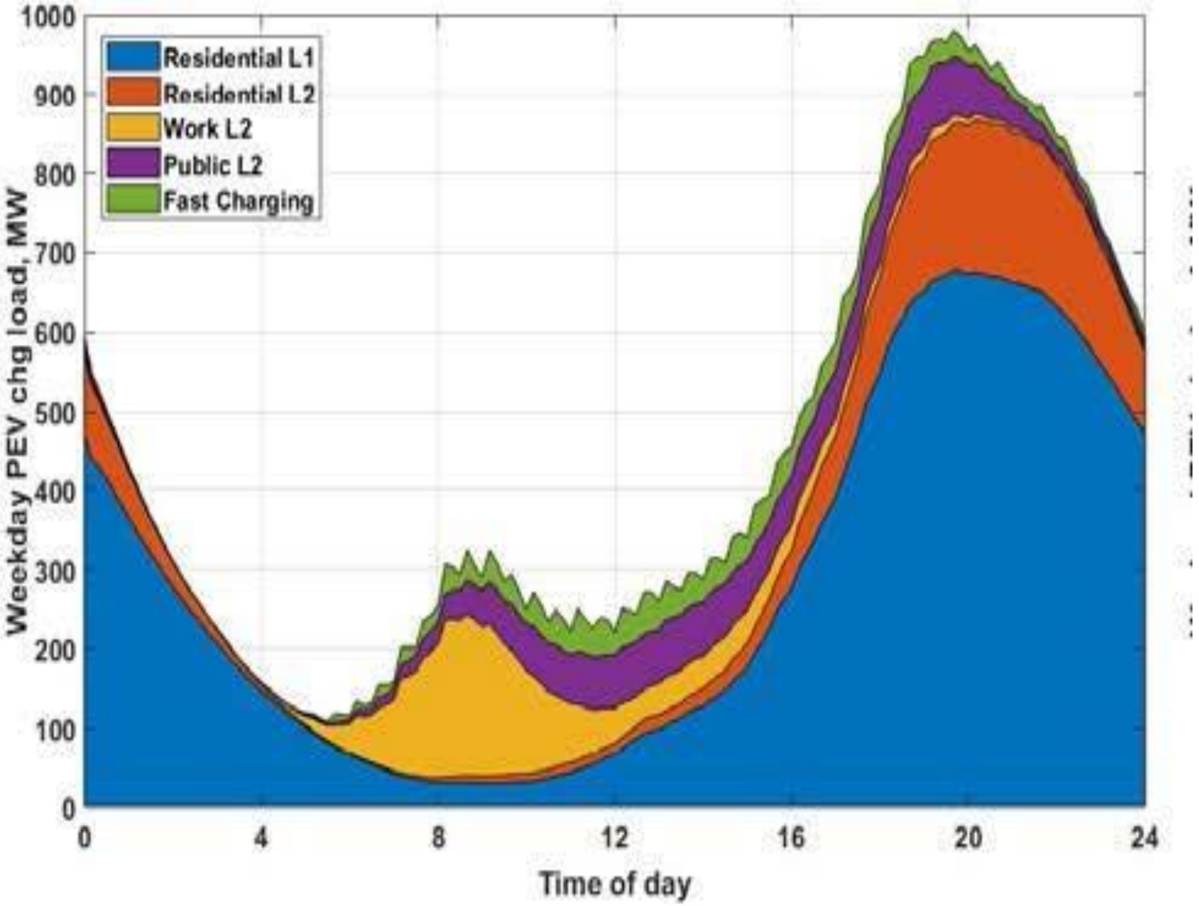


Transportation Fuel Options and Challenges

Vehicle Fuel Options	Challenges
Biofuels	Need large biorefineries to lower costs
Electric	Not viable for long-range aircraft Massive grid challenge Not viable for heavy trucks
Hydrogen	Low-cost production Penalties for aircraft, heavy trucks Massive new infrastructure
Hybrid (Electric + Fuel)	Avoids many challenges

California Plug-In Electric Vehicle Charging Load Profile By 2025: Big Trouble for Grid

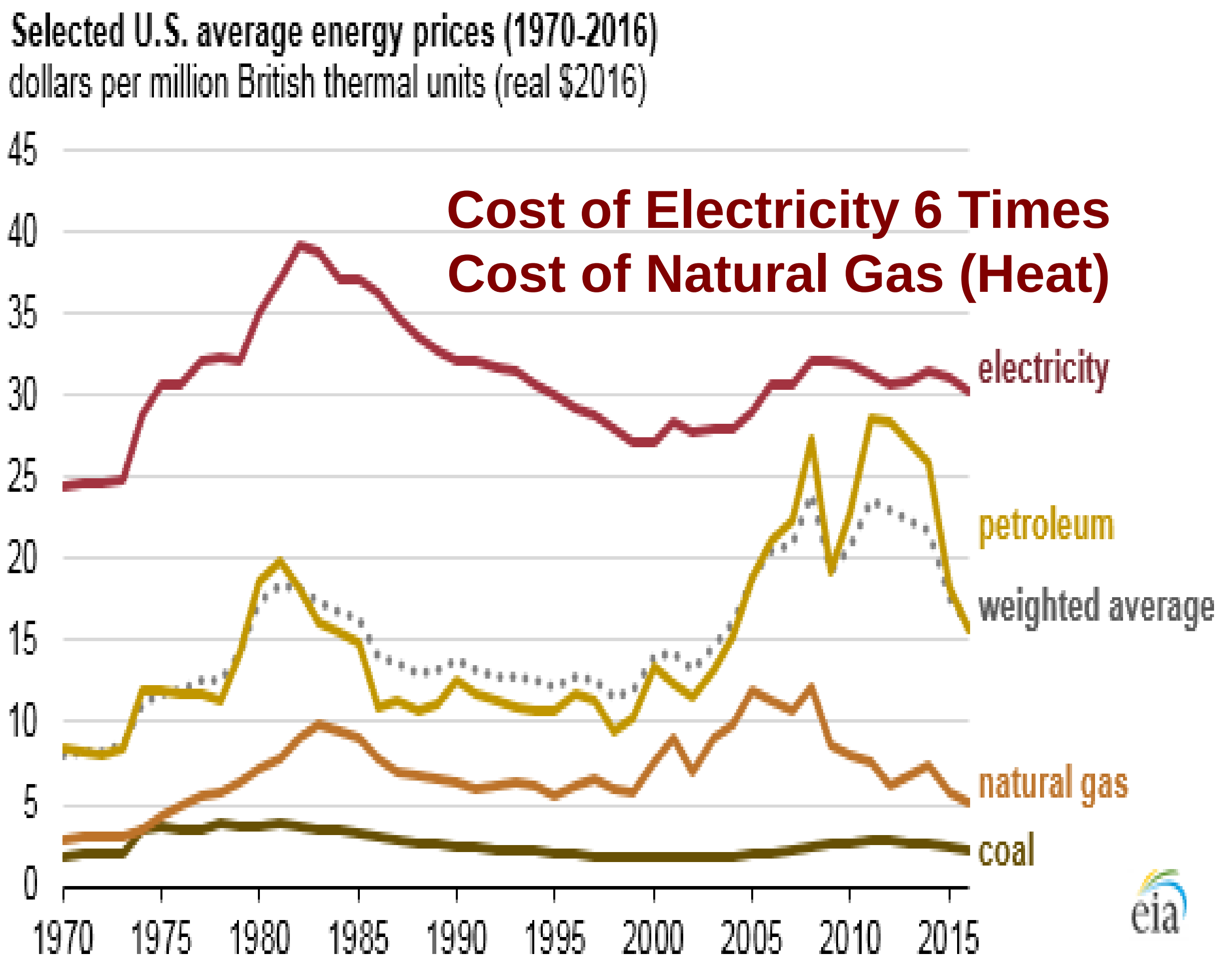
- Single-car families charge vehicles in the early evening so car is available
- **Peak charging at times of peak electricity demand implying BEVs are the nightmare grid scenario**
- Plug-in hybrid cars (batteries plus internal combustion engine) help grid
  - Car always available
  - Charge when electricity prices are low
  - Smaller (cheaper) battery pack
- **Will grid constraints limit all-electric vehicles to small fraction of the fleet?**



California Energy Commission Staff Report - CA Plug-In Electric Vehicle Infrastructure Projections 2017-2025

Electricity is Six Times More Expensive Than Heat

- Massive cost challenge to electrically heat homes in cold climates: Extreme peak demand for limited number of hours per year and very expensive
- Challenge for anywhere where one needs high instantaneous energy delivery
- **Incentives for drop-in storable biofuels**



Large-scale Nuclear, Electric, Hydrogen, Biofuels System Design

Building a Low-Carbon World is a Systems Challenge
It is a Chemical, Mechanical and Nuclear Engineering Challenge

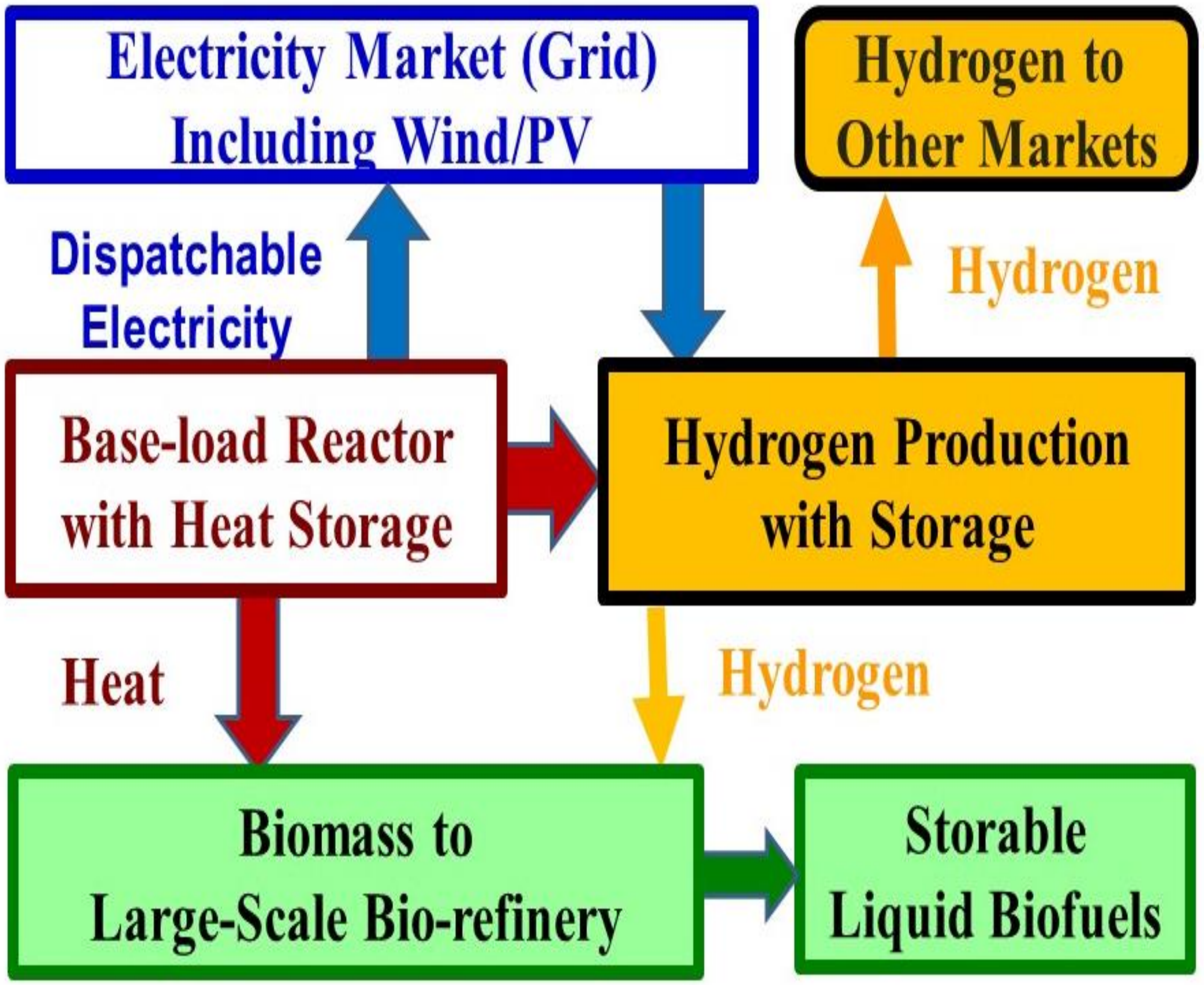
Design Goal: Low-Carbon Replacement of Fossil Fuels

- Cost, transportability and storeability of fossil fuels moved billions of people to the middle class
- Flat-price energy world where cost of fossil fuels the same in New York harbor as Shanghai
- Before fossil fuels, local standards of living depended upon local availability of energy resources. In the middle ages:
  - England was rich: (1) good soils to feed people and animals and (2) mild winters
  - Scandinavia was poor: (1) low-quality soils and (2) harsh winters with heat demand

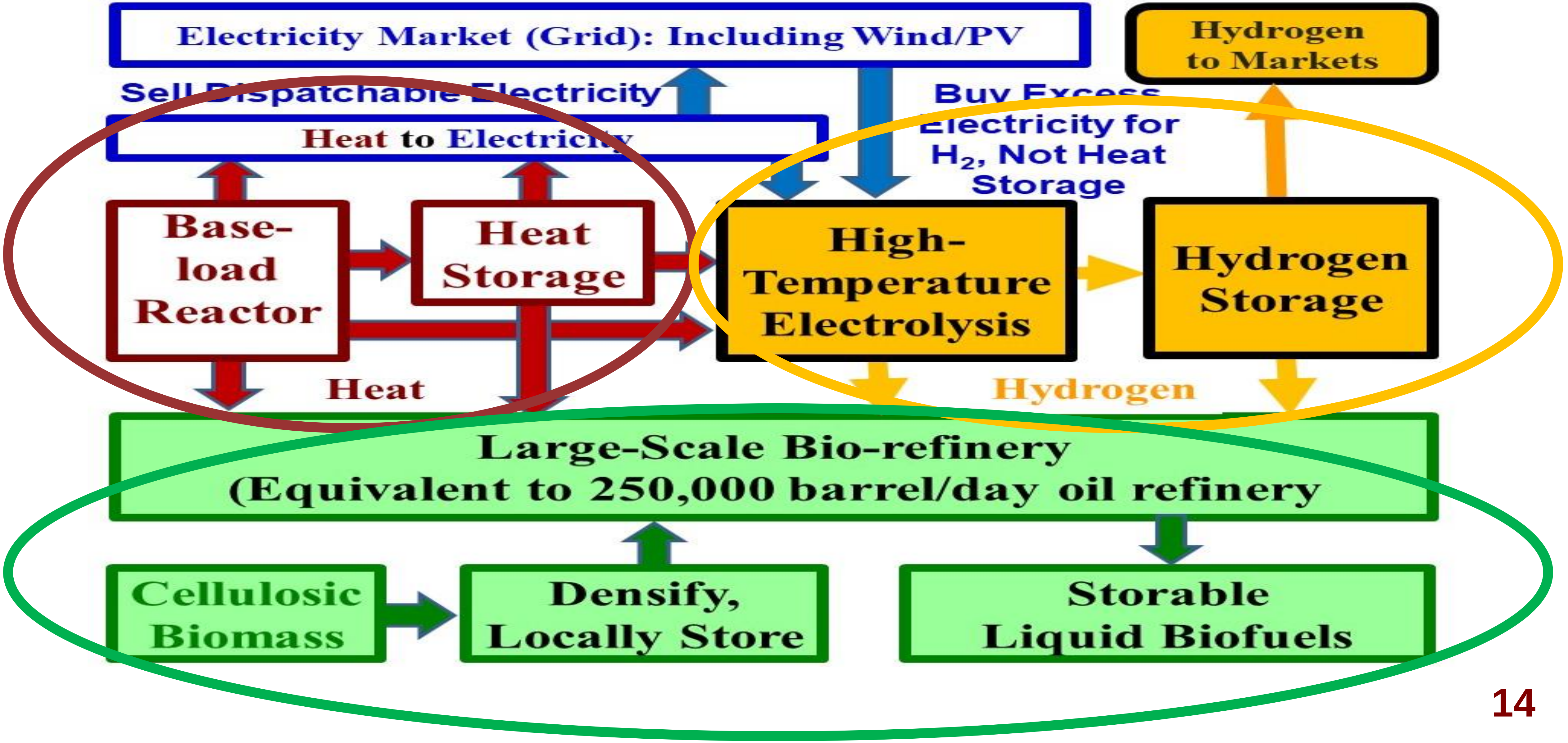
- Replacement system uses local resources (solar, wind, hydro, geothermal, etc.) where economic but not dependent upon those resources

Large Scale Energy System Design

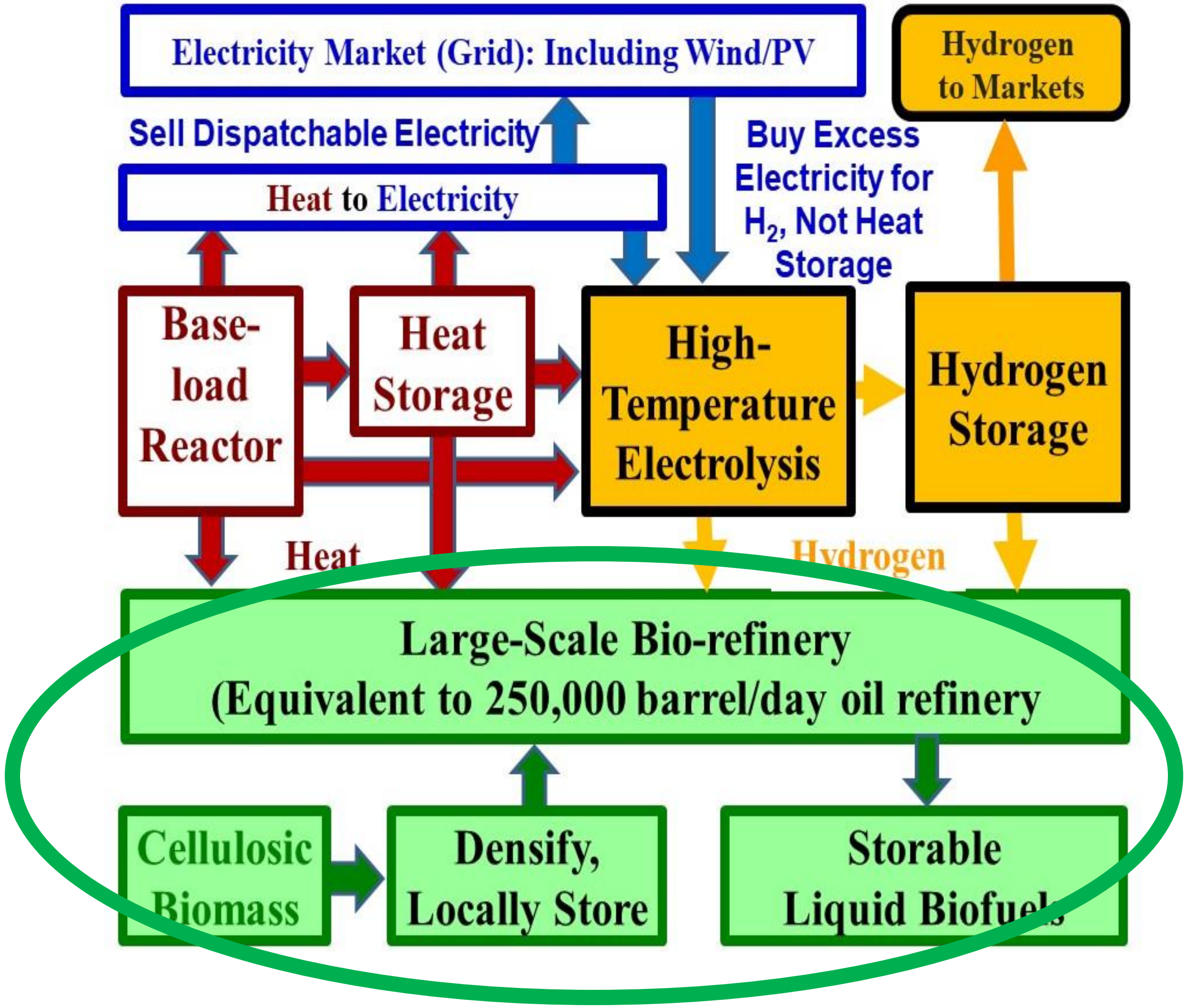
- System produces three products
  - Dispatchable electricity
  - Dispatchable hydrogen
  - Liquid biofuels
- High capacity factors for high-capital-cost systems
  - Nuclear, wind and solar
  - Hydrogen production system
  - Biorefinery
- Four low-cost energy storage systems: (1) heat, (2) hydrogen, (3) densified biomass and (4) liquid biofuels
- Reactor, heat storage, hydrogen production and bio-refinery collocated to enable heat integration



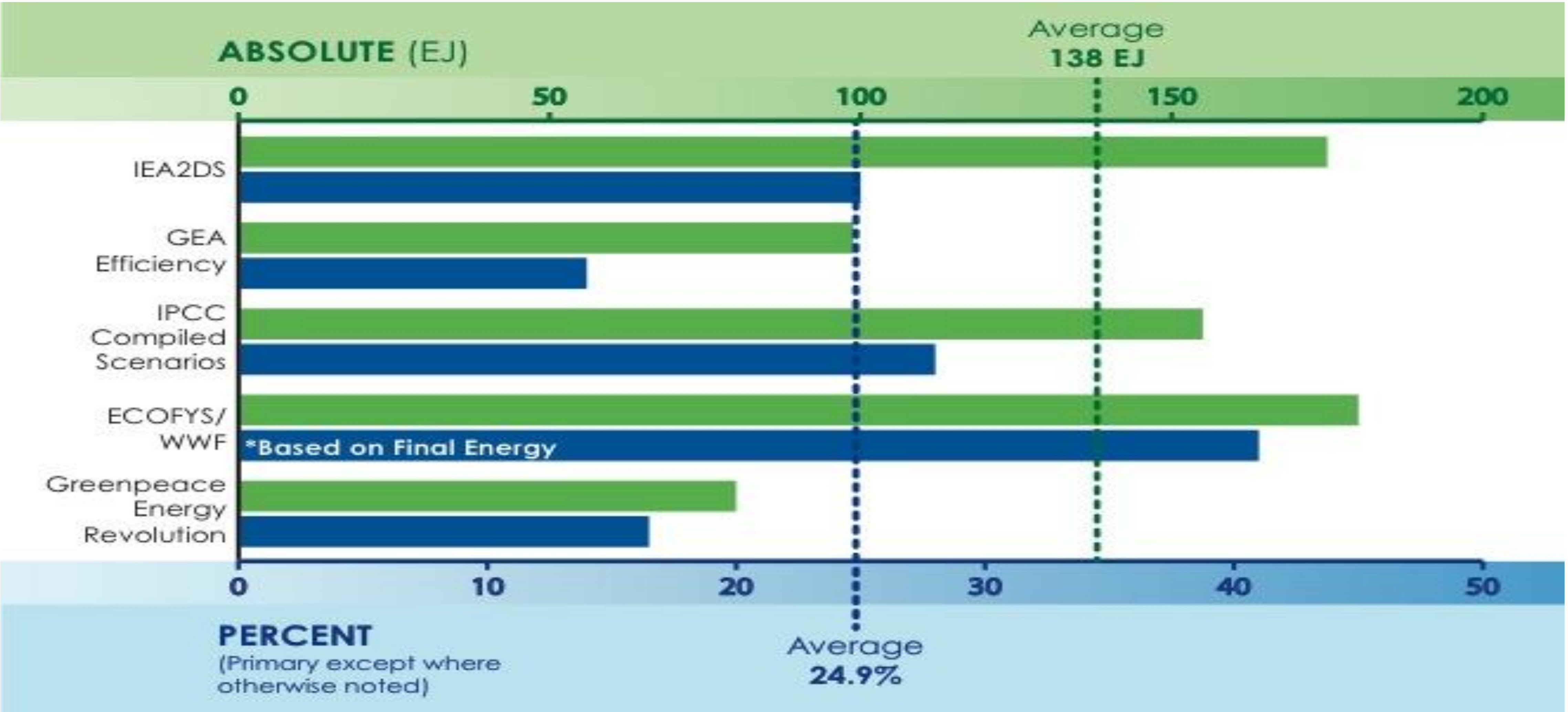
Major System Components: Three Major Subsystems



Low-Carbon Large-Scale Biofuels With Heat and Hydrogen Input



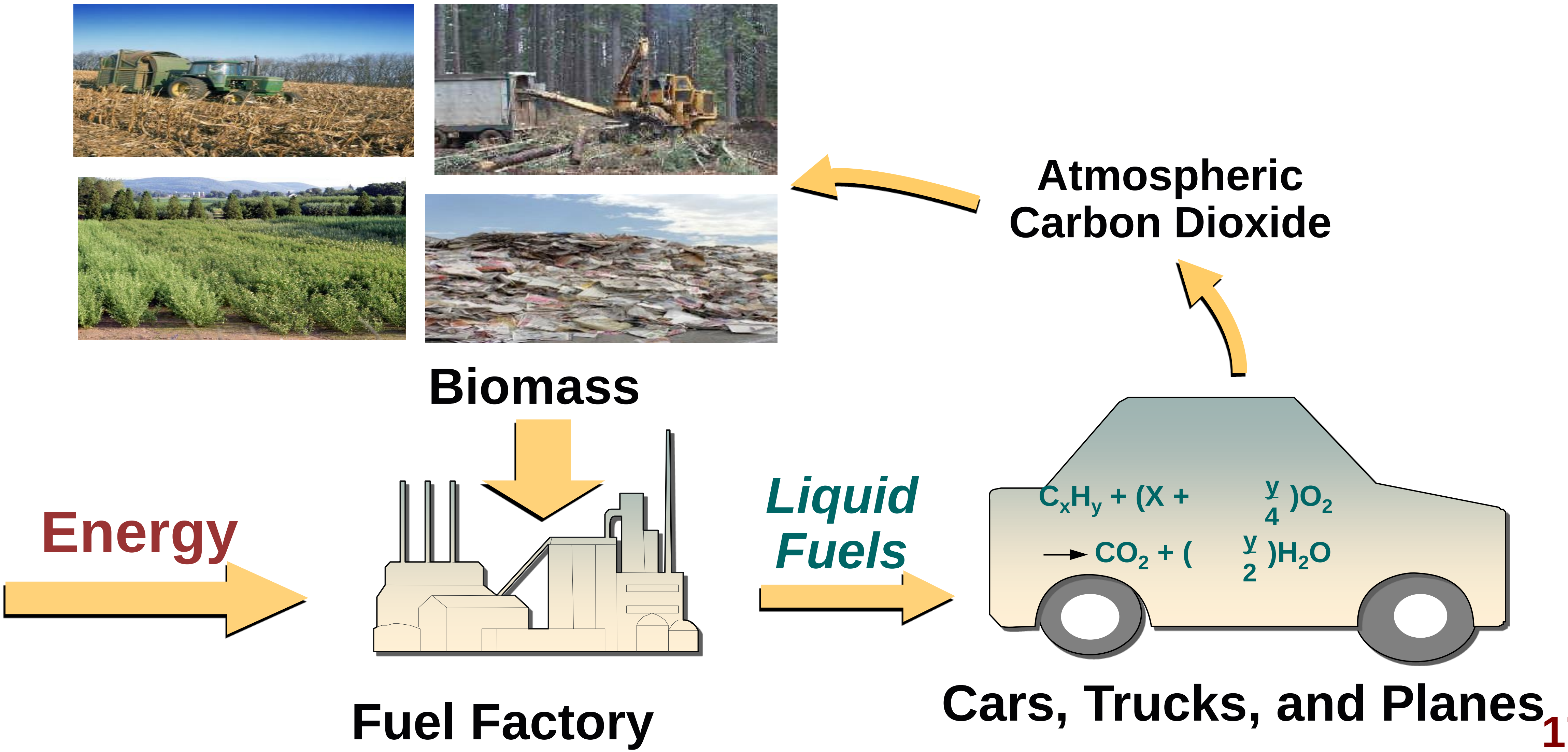
Bioenergy Contribution in 2050: Five Low-Carbon Energy Scenarios Suggest Could Meet Quarter of Global Energy Needs



 Dale et al., ES&T, 2014

External Energy Sources Increase Liquid Fuel Yields Per Ton of Biomass

Burn Biomass or Supply External Energy Heat/H_2 for Biorefinery



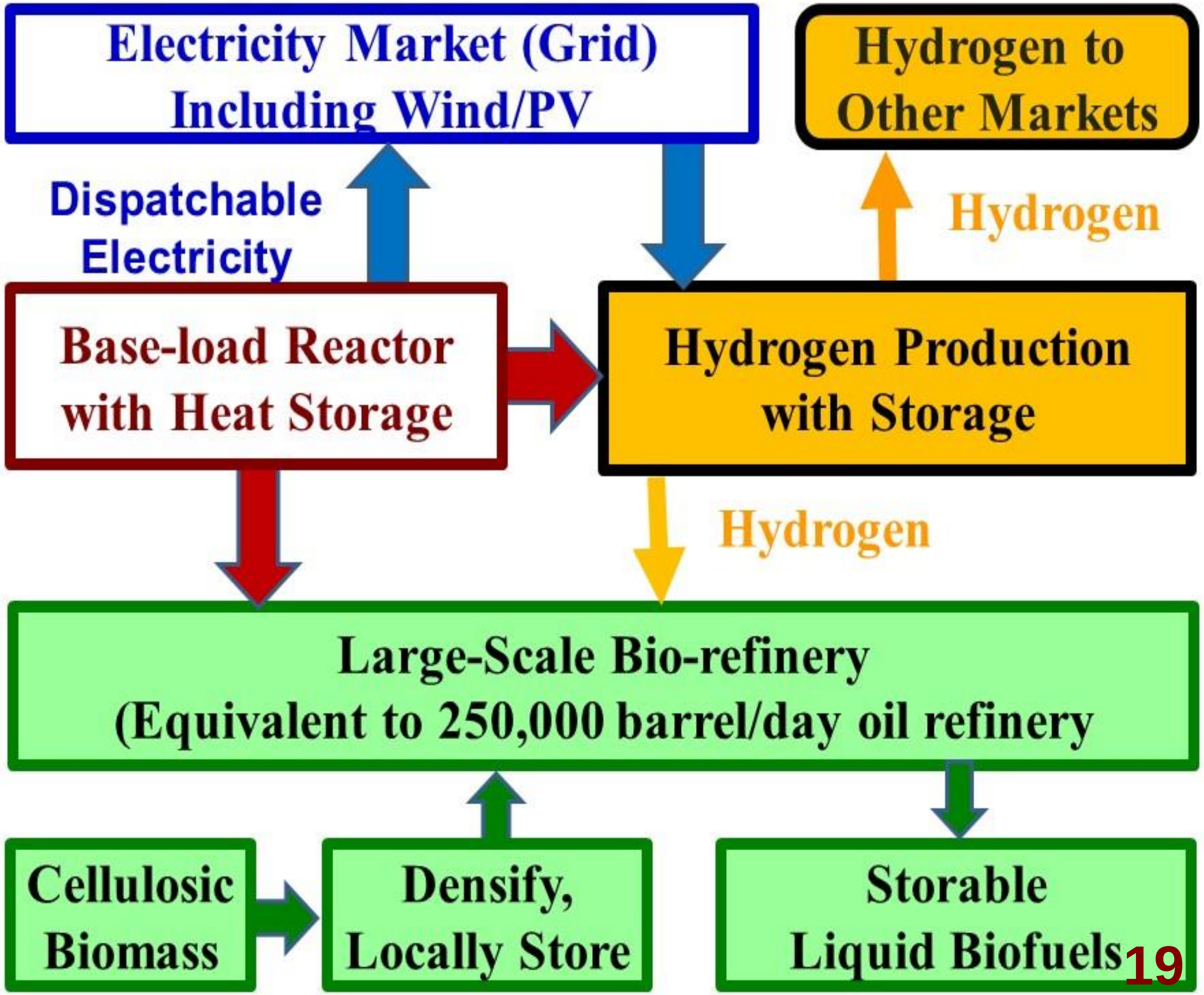
Future Biofuels Options May Use Massive Quantities of Hydrogen

Comparing Options to Produce Hydrocarbon Fuels from Biomass		
Platform	Yield, Kg Octane per Kg Cellulose	Input Energy from Hydrogen (%)
Thermochemical	**0.310**	0
Sugar	**0.352**	4.9
Carboxylate (Kolbe)	**0.422**	23.4
Carboxylate (2°Alcohol)	**0.469**	32.3
Carboxylate (1° Alcohol)	**0.528**	40.8

Almost Double Liquid Fuels per Ton of Biomass and Higher-Quality Fuel with Hydrogen Addition

Large-Scale Nuclear Heat Hydrogen Biofuels System

- Cellulosic biomass converted to densified intermediate product near source of raw biomass
  - Stable and cheap to store
  - Economic to ship long distances
- Large biorefinery with large heat and hydrogen inputs to maximize output of high-quality biofuels
- Heat (gigawatts) and hydrogen from nuclear plants to minimize costs and carbon dioxide emissions



Need for Storable High-Density Biomass Intermediate Product

- Current cellulosic biomass forms have major challenges (bales, chipped wood, etc.)
  - Low density, expensive to store
  - Degrade in storage
  - Expensive to transport further than 20 to 50 miles
- Storage and transport limits result in small inefficient biofuels plants with lower capacity factors with higher cost biofuels
- Several promising densification technologies but none deployed at scale; not build large biorefinery until densification facilities but not build densification facilities until market for densified biomass

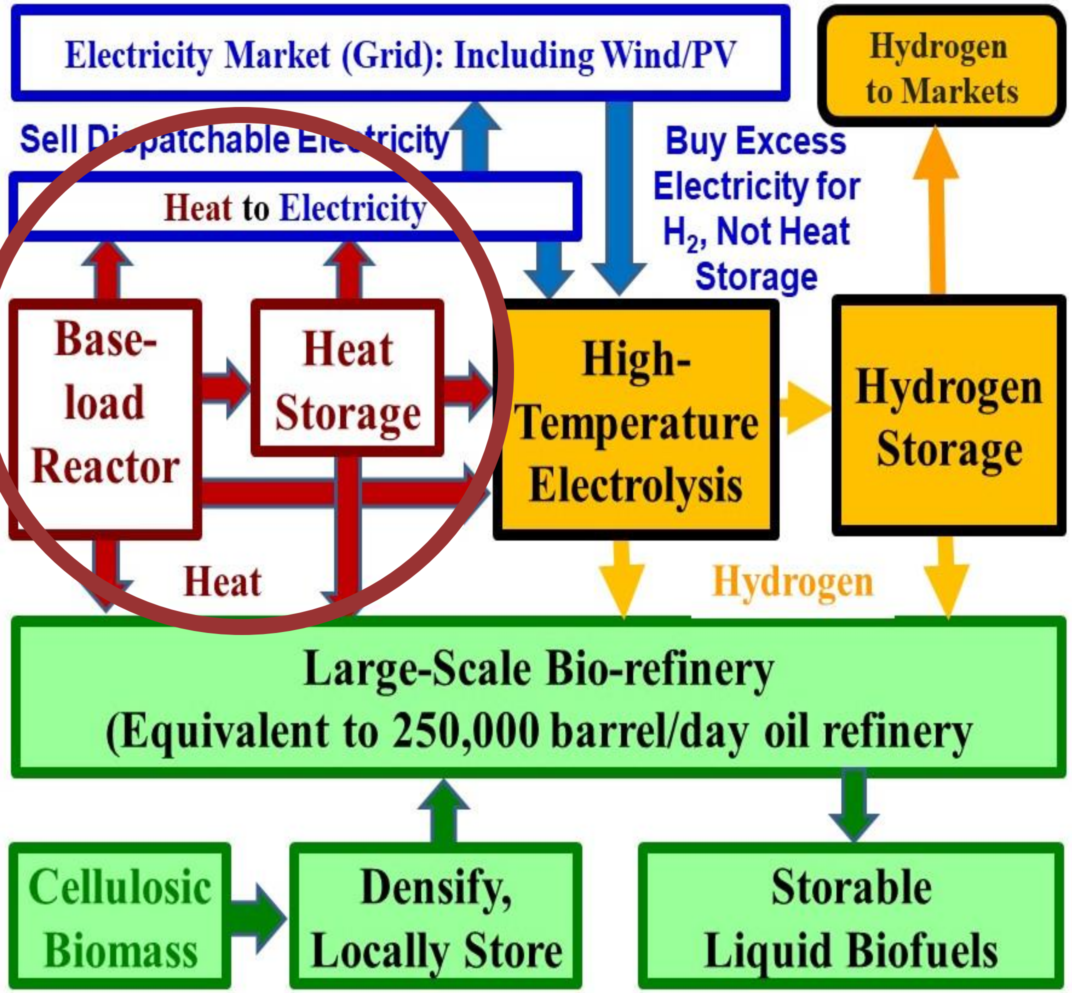
Require Large-scale Cellulosic Biorefineries

- Little development because no deployed system to deliver high-density storable cellulosic feedstock at required scale
- Massive economic incentives for large plants at least equivalent to 250,000 barrel per day oil refinery
  - Massive economics of scale
  - More high-quality product per ton of feedstock
    - Secondary streams upgraded into fuels
    - Enables large-scale low-carbon-footprint nuclear heat and hydrogen
- The history of oil refining showed massive reductions in cost and reduced waste streams with larger refineries over time
- If can deliver high-volume feedstock, enables major oil companies to fully engage and develop large biorefineries: oil companies are very good at chemical process development and large-scale project management

Nuclear System with

Heat Storage for Variable

Electricity and Heat

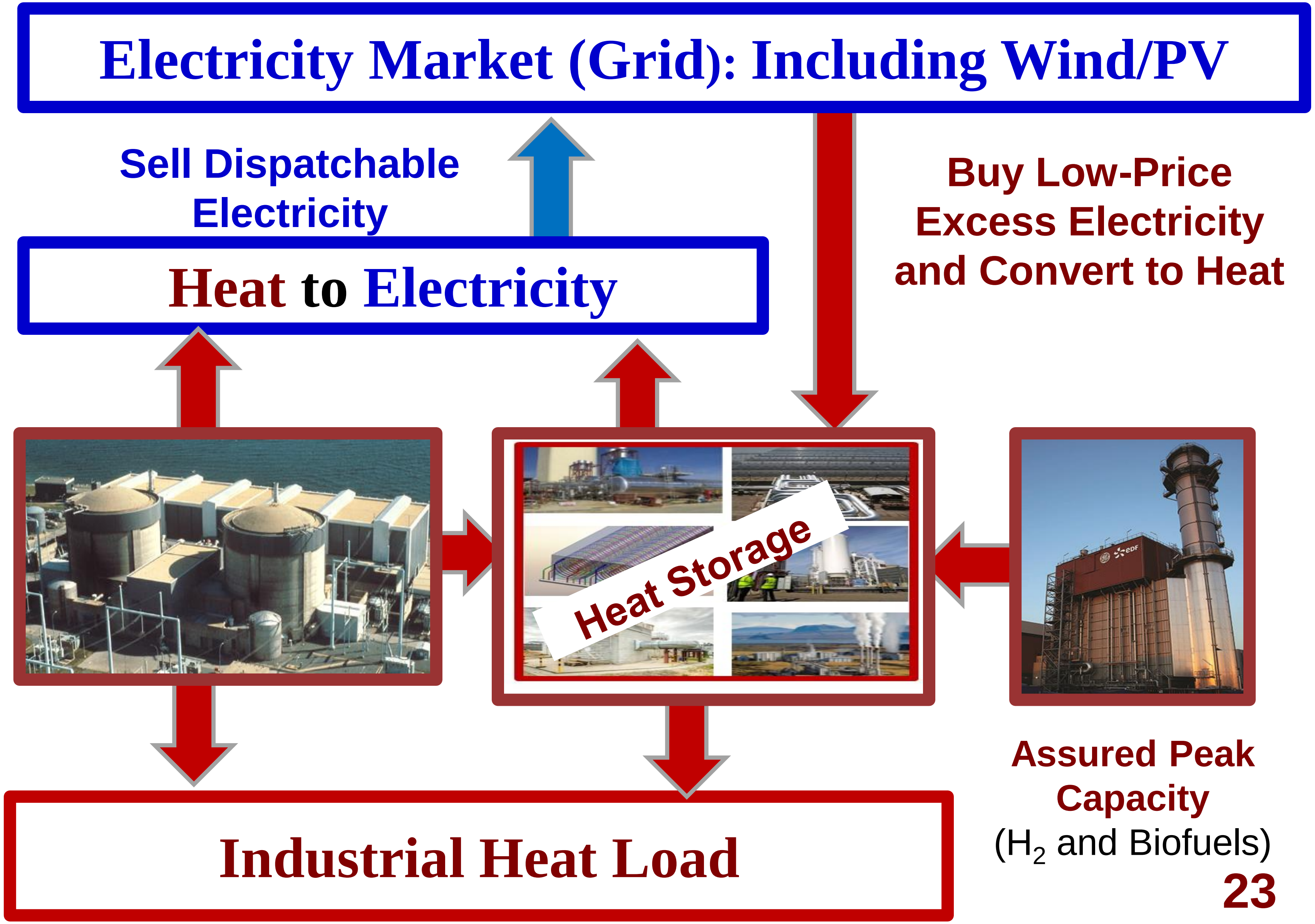


Enabling Inputs into Low-Cost Biofuels

Enabling Technology for Large-scale Wind and solar

Require a New Low-Carbon System Design

- Base-load energy production (Nuclear, wind, PV)
- Heat storage enables variable electricity output
  - Fraction of base load
  - Multiple of base load
- Low-price (excess) electricity (wind/PV) to heat storage
- Backup furnace for assured peak capacity



Heat Storage Is Cheaper than Electricity Storage (Batteries, Pumped Hydro, etc.) with Many Technology Options

- DOE heat storage goal: $15/kwh(t) but new technologies may be much cheaper
- Battery goal $150/kWh(e), double if include electronics
- **Difference is raw materials cost**
- **EPRI: batteries are 3 to 4 times more expensive per kWh(e)**

Storage Technologies (*Italic CSP Commercial*)	**LWR Option**	**Sodium, Salt, Helium Options**
Pressurized Water	X	Limited
Geothermal	X	Limited
Counter Current Sat Steam	X	Limited
Cryogenic Air	X	X
Concrete	X	X
Crushed Rock	**X**	**X**
Sand		X
Oil	X	Limited
Cast Iron		X
Nitrate Salt		*X*
Chloride Salt		X
Graphite (Helium and Salt)		X

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Nitrate-Salt Heat Storage is Done at the Gigawatt-hour Scale at Concentrated Solar Power Plants

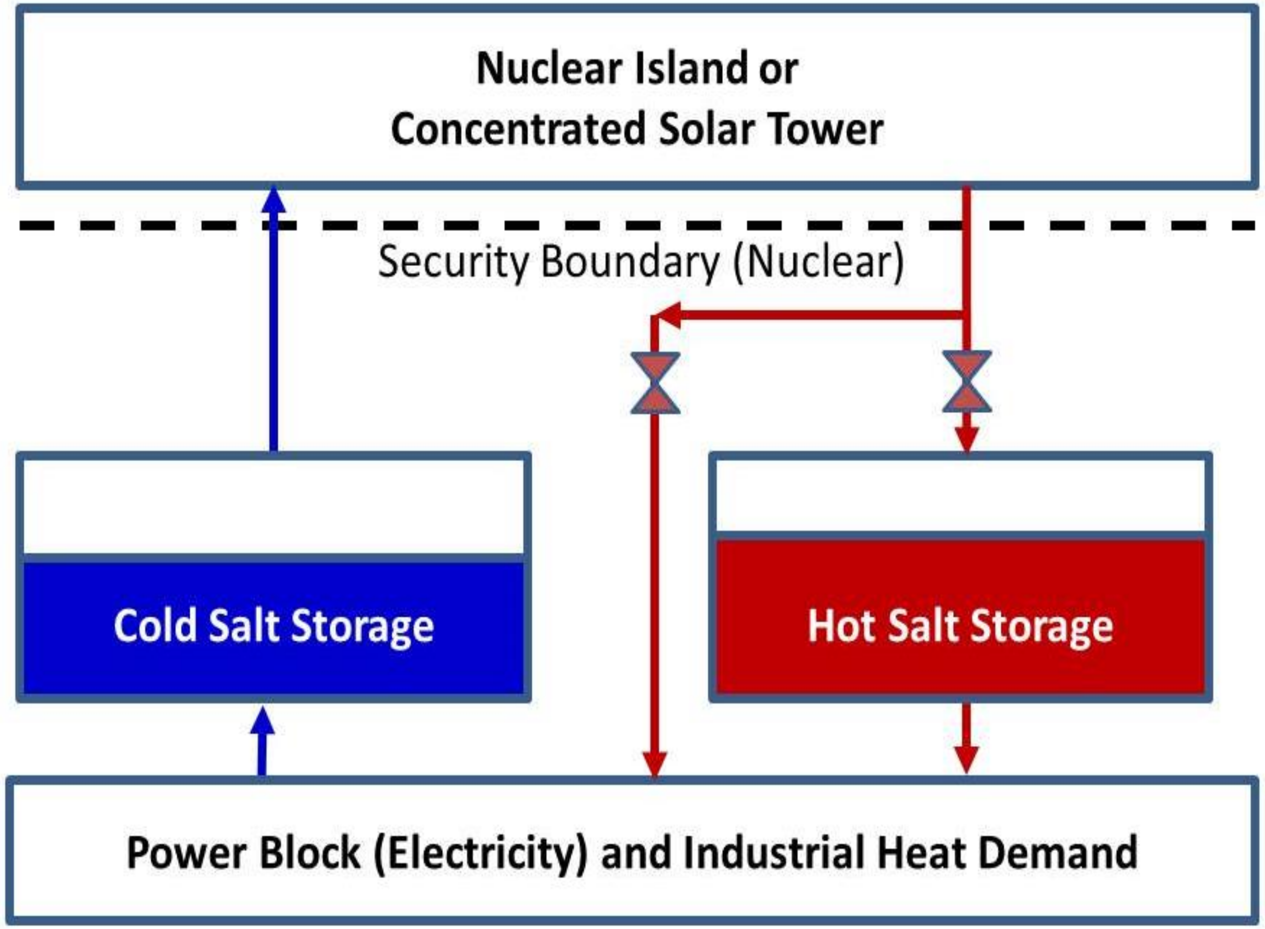
Nitrate Salt Heat Storage Proposed for Sodium, Salt and Helium Cooled Reactors

Solana Generating Station (2013, U.S., ~4200 MWh(t))

Cerro Dominador Project (*under construction*, Chile, ~4800 MWh(t))

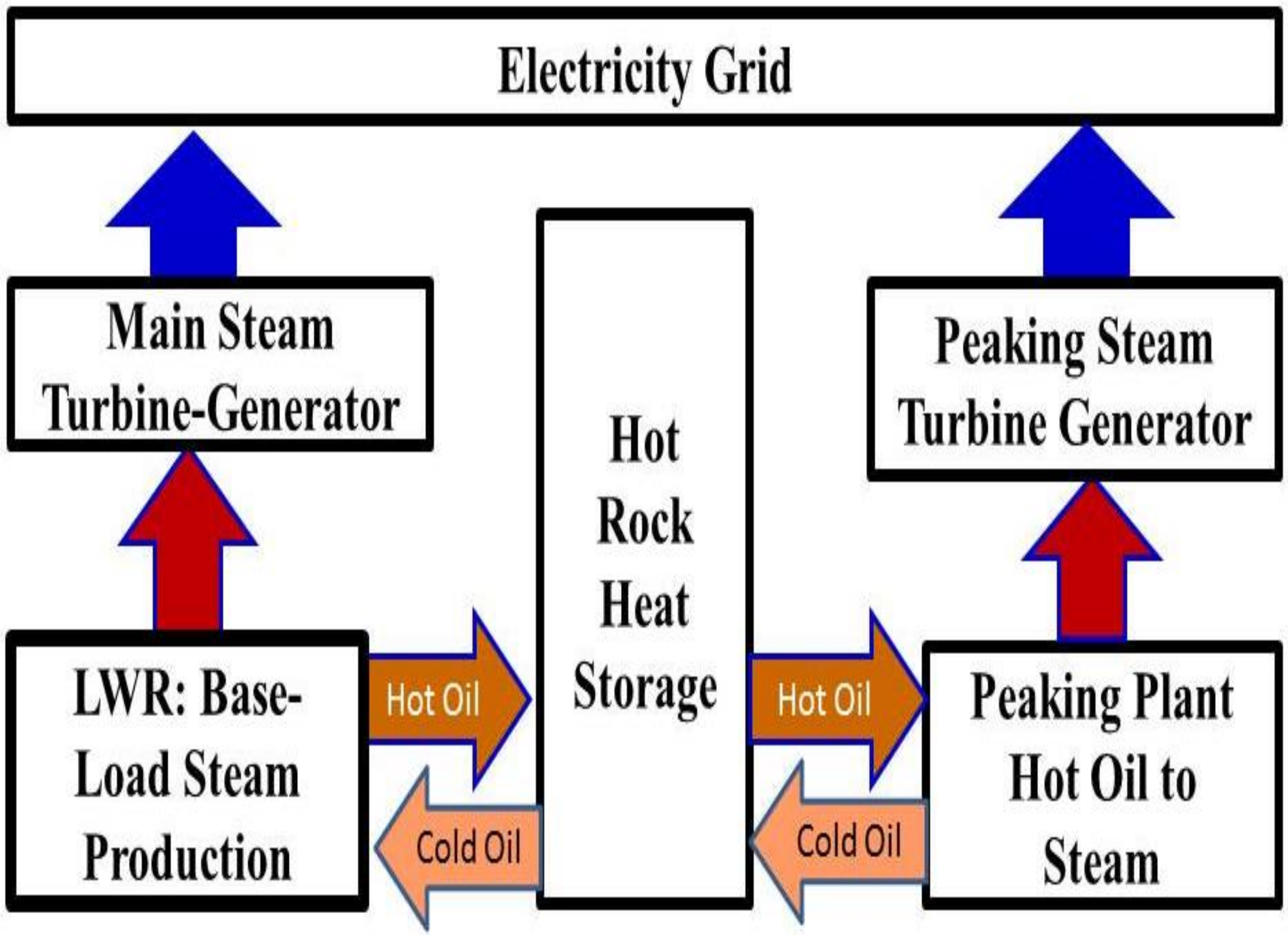
Change In Energy System May Result In a Different Plant Design: Heat Source Separated From Power Block

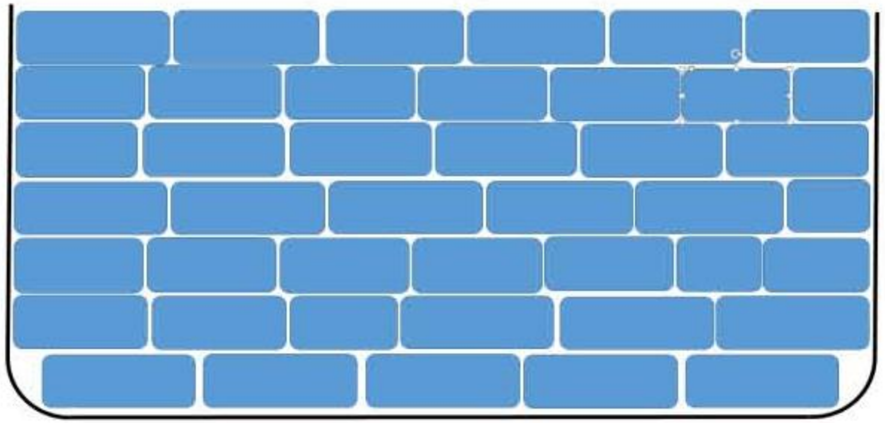
- Most salt and some sodium reactor designs propose a nitrate loop to separate low-pressure reactor from high-pressure power cycle
- **No efficiency loss for heat storage—already have nitrate loop**
- Batteries and other systems have significant losses moving energy in and out of storage



Lower-Temperature Light-Water Reactor Heat Storage Using Crushed Rock and Hot Oil

- Hot oil for heat transfer between heat storage system and steam cycle

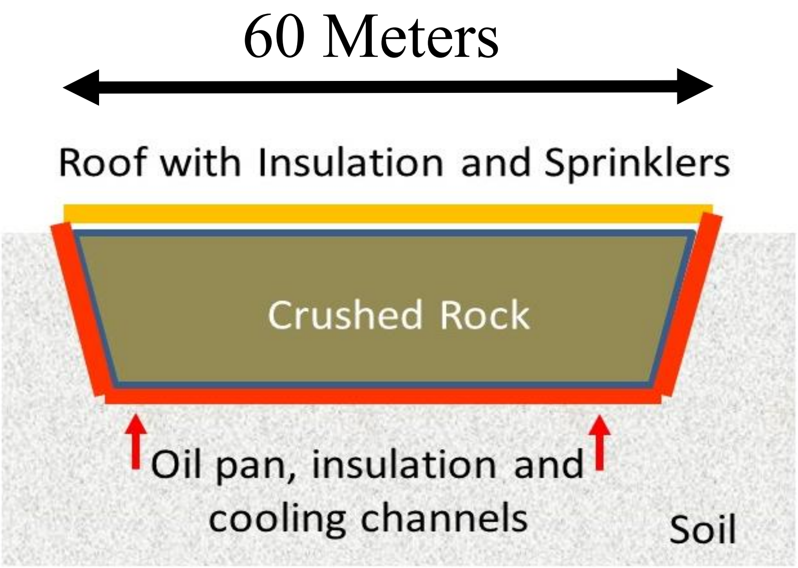


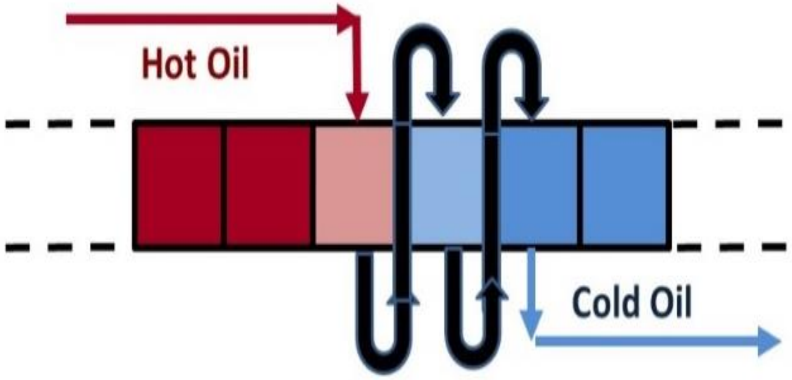


Korean Design: Large barge (60 by 450m) with multiple tanks for 20 GWh(e) heat storage: Supertanker technology

Driving Down Hot-Rock Heat-Storage Costs (MIT)

- Heat Storage: Single Trench Storage Container
  - 60 m wide by 20+ meter high
  - 100 to 1000 meters long (gigawatt day to gigawatt-week
  - Minimize surface (expensive steel and insulation) to volume (cheap crushed hot rock) ratio
- Hot oil heat transfer by sprinkling oil over rock
  - Sequential heating and cooling of crushed rock
  - Heat-transfer oil inventory determined by maximum rate of heat transfer to and from storage—not heat storage capacity

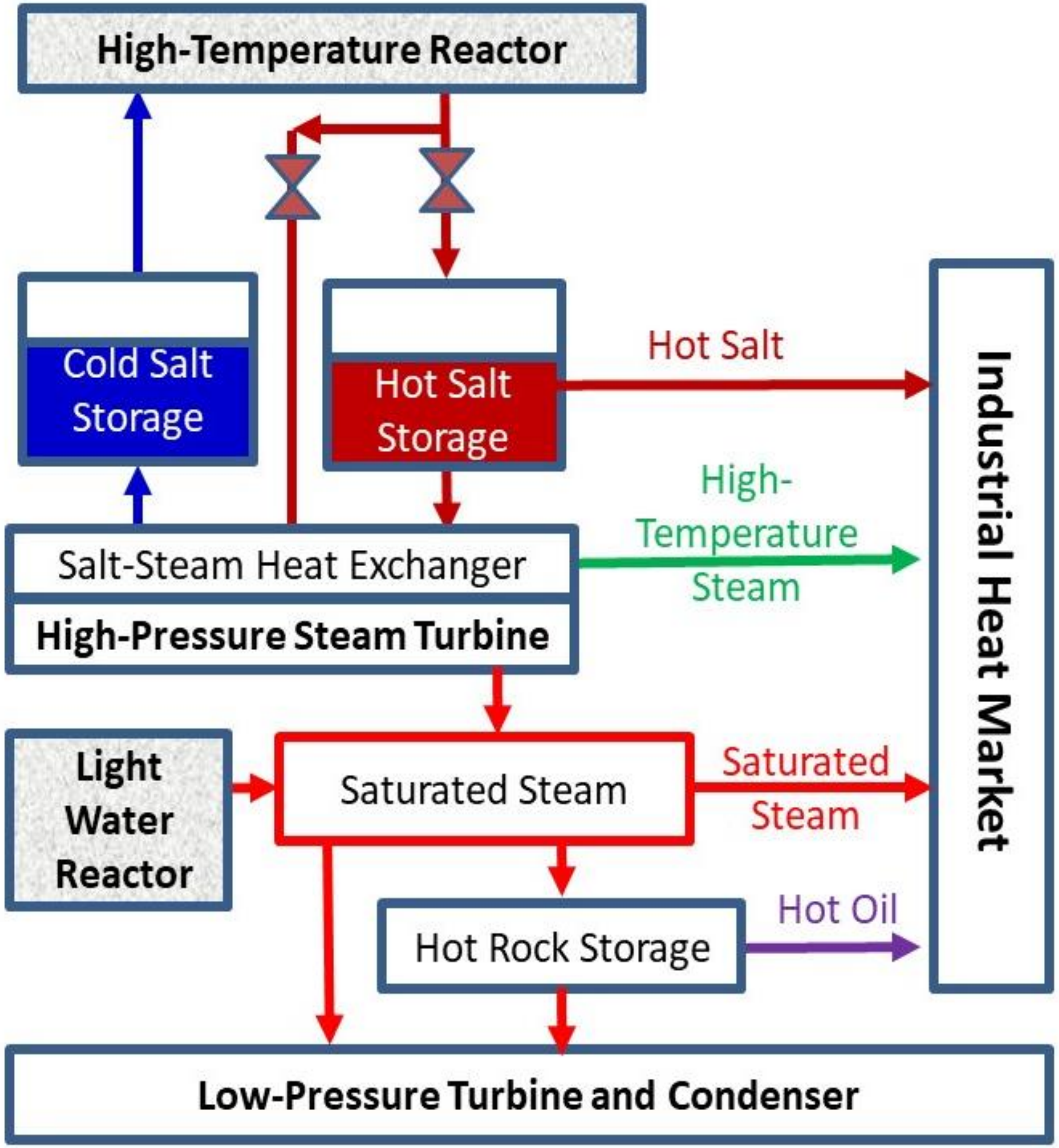




Can We Drive Incremental Heat-Storage Capital Cost Below $1/kWHr?

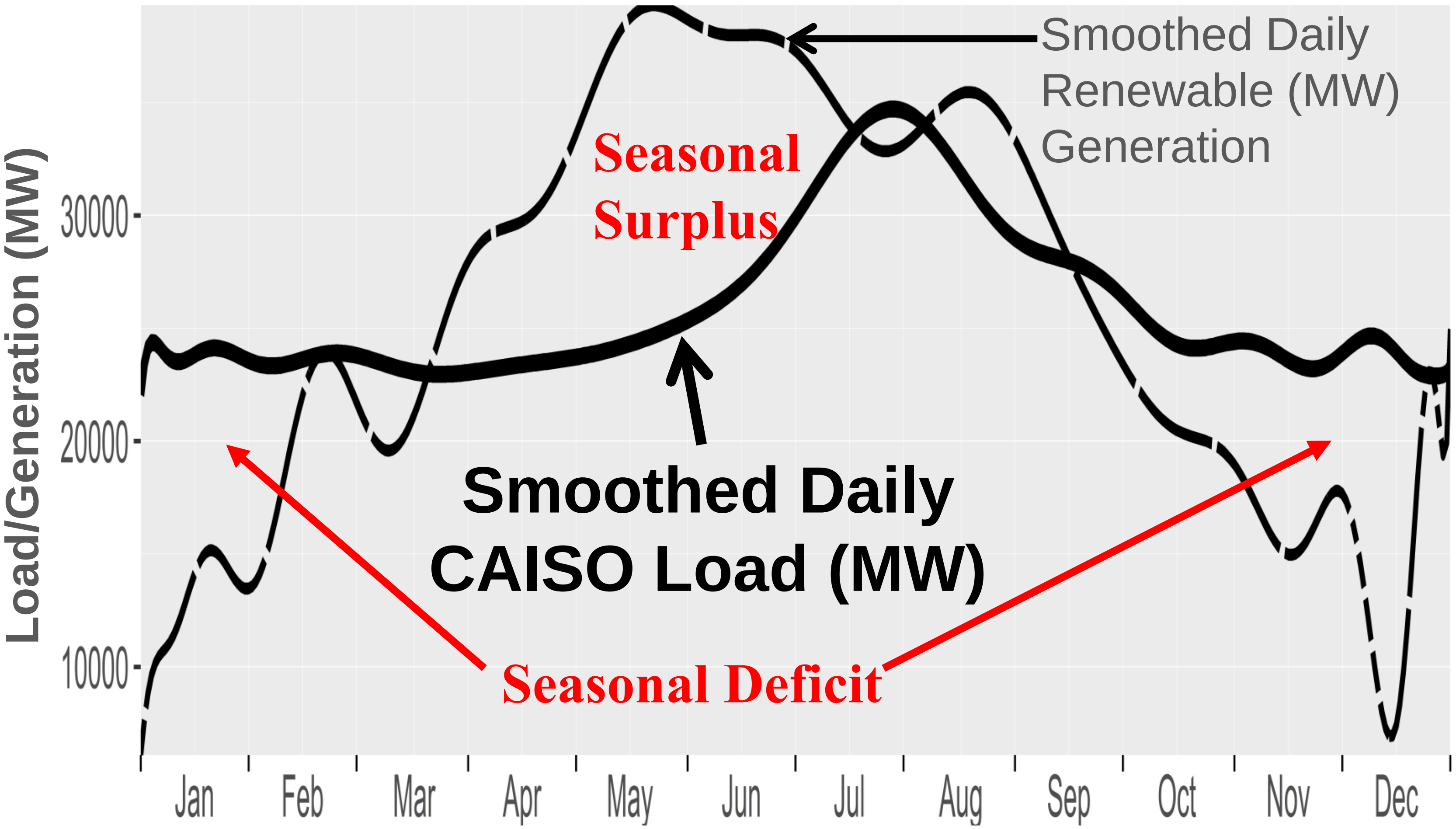
Heat Storage for High-Temperature Reactors and Light- Water Reactors

- For HTRs, Two Storage Locations
- LWRs Require Lower-Temperature Storage Systems
- Example: Salt (high temperature) and Hot-Rock (lower temperature) Heat Storage

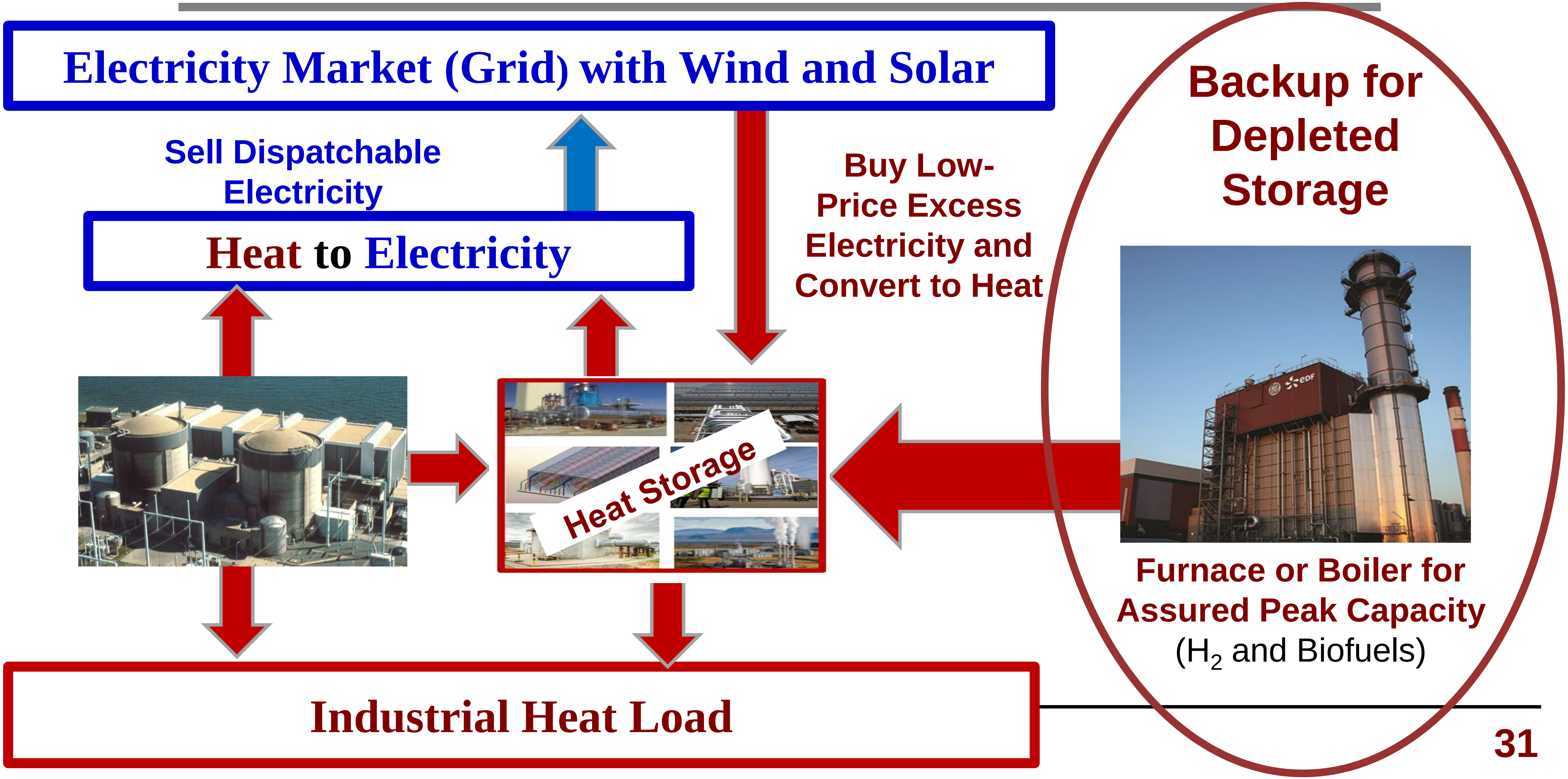


Challenge of Seasonal Mismatch Between Production and Demand if Just Use Renewables: California Example

- Build renewables output to match annual consumption (net zero)
- Seasonal mismatch between production and demand
- Flat nuclear production profile closer to demand but still mismatch



Require Assured Generating Capacity



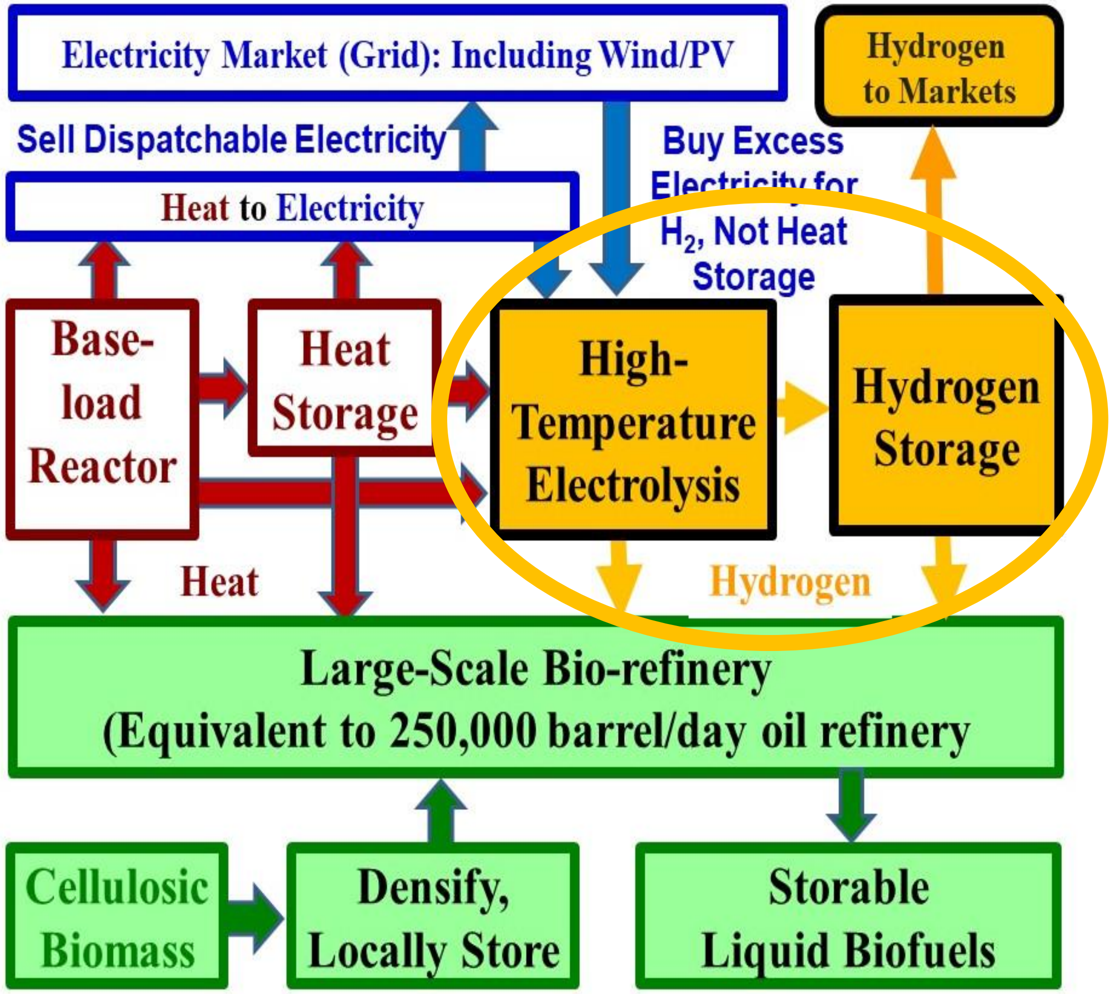
If Heat Storage, Option to Buy Furnace or Steam Generator for Assured Peak Power

- All storage devices can become depleted but need assured peak power
- Burns (1) natural gas or (2) low-carbon biofuels and hydrogen with heat to storage system
- Low-cost option
  - Use heat-storage electricity peaking capability (turbine generator)
  - Half to third the cost of backup gas turbine for assured generating capacity

Hydrogen Production

Chemical Feedstock for Biofuels and Industry

Energy Carrier with Low-Cost Storage



Large Existing Hydrogen Market: Large Growth for All Low-Carbon Futures

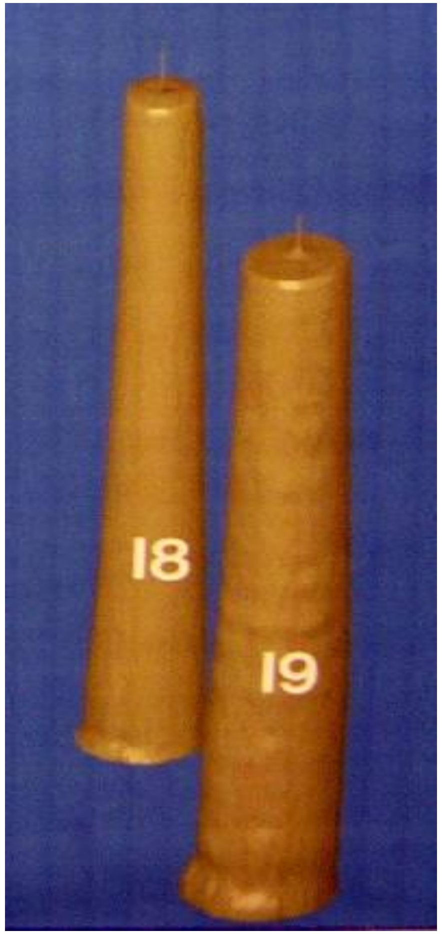
- Existing markets (10 million tons/y)
  - Fertilizer
  - Refineries
  - Chemicals and specialty metals
- Added hydrogen markets in a low-carbon world
  - Replace fossil fuels as chemical reducing agent to produce iron and other metals
  - Very high-temperature furnaces
- Biofuel upgrade to gasoline, diesel and jet fuel

Potentially 15 to 30% of all Energy Consumption

Large-Scale Hydrogen Storage Is Cheap

- Hydrogen stored in same types of underground facilities used for natural gas
  - We store up to 20% of a year's supply of natural gas
  - Very cheap bulk storage
- Expensive to store a few kilograms of hydrogen for a fuel-cell car

Chevron-Phillips H_2 Clemens Terminal (160' X 1,000' Cylinder Salt Cavern)

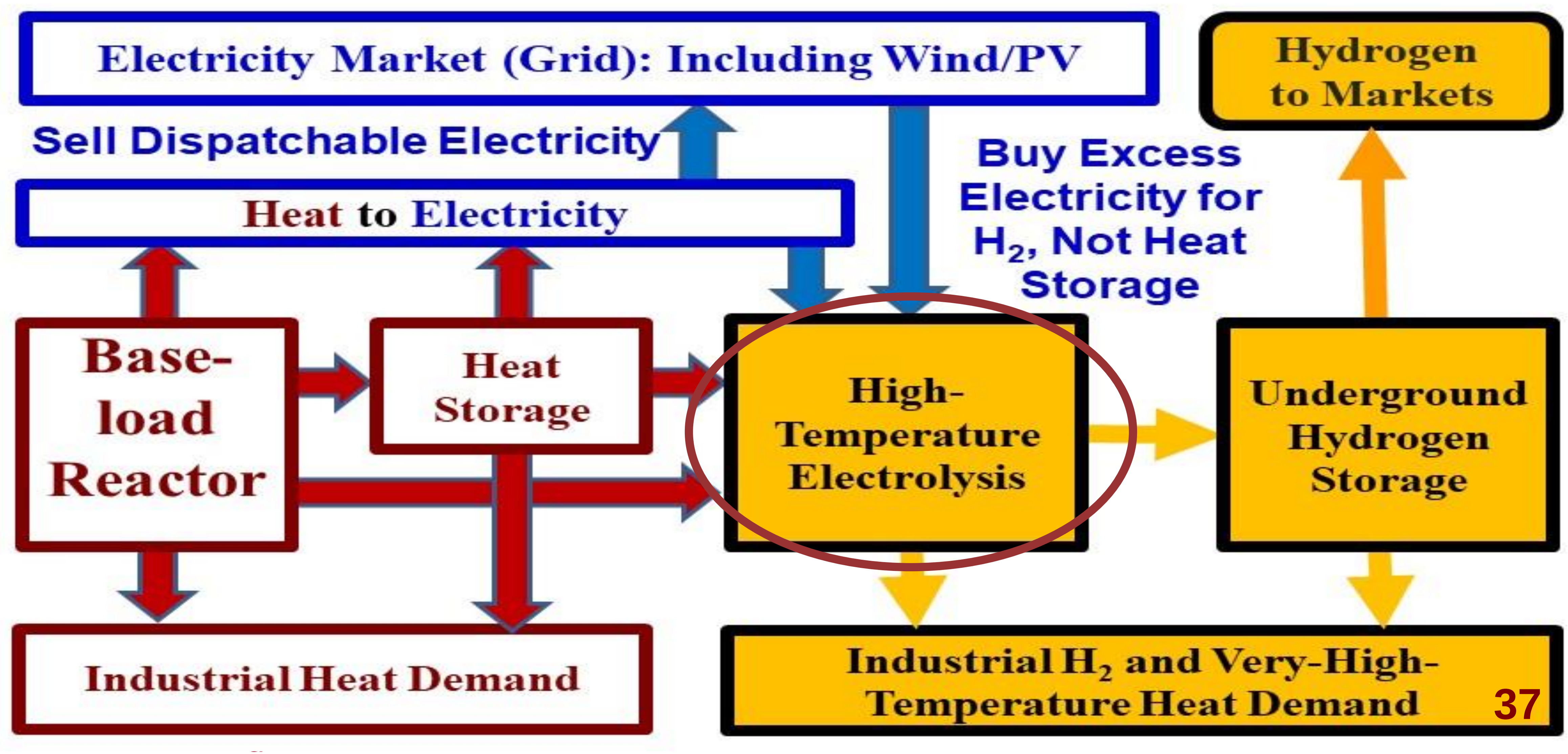


Low-Carbon Hydrogen Production Methods Are Capital Intensive: Plants Must Operate at High Capacity Factors for Affordable Hydrogen

- Electrolysis: Electricity plus water
- High-temperature electrolysis: Likely low-cost option
  - Steam electrolysis so part of energy input is lower-cost heat
  - No expensive catalysts because of higher temperatures
- Thermochemical: Heat plus water
- Steam methane reforming of natural gas (current hydrogen production technology) with added carbon dioxide sequestration
  - Likely low-cost option where cheap natural gas and good sequestration sites
  - Texas, Texas and Texas

Hydrogen Is a Premium Energy Carrier Like Electricity

Low-Cost Hydrogen and Heat Storage Enables Economic Variable Hydrogen-Heat-Electricity Production System



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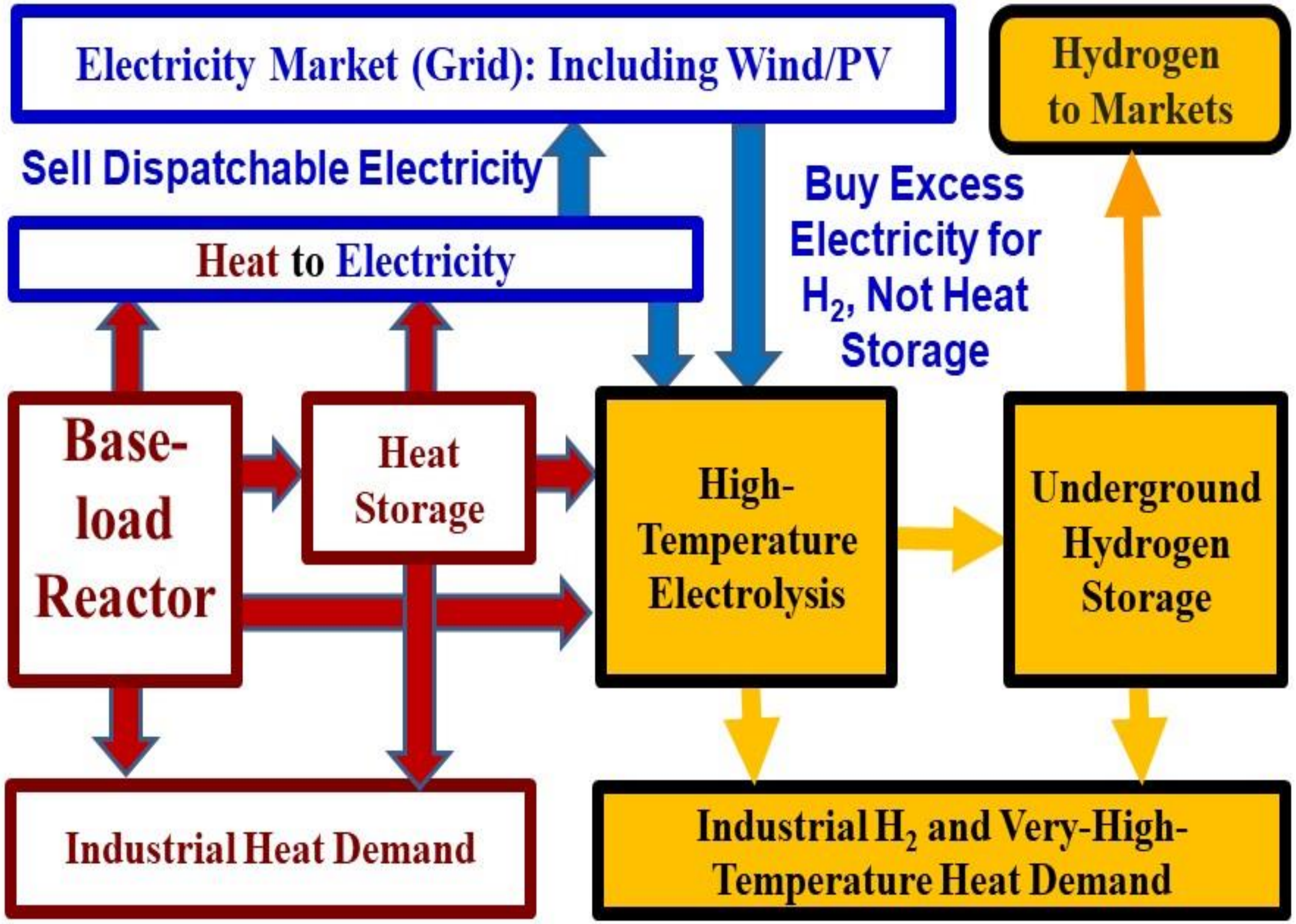
The Hydrogen-Heat-Electricity System Uses Excess Low-Cost Electricity to Make Hydrogen

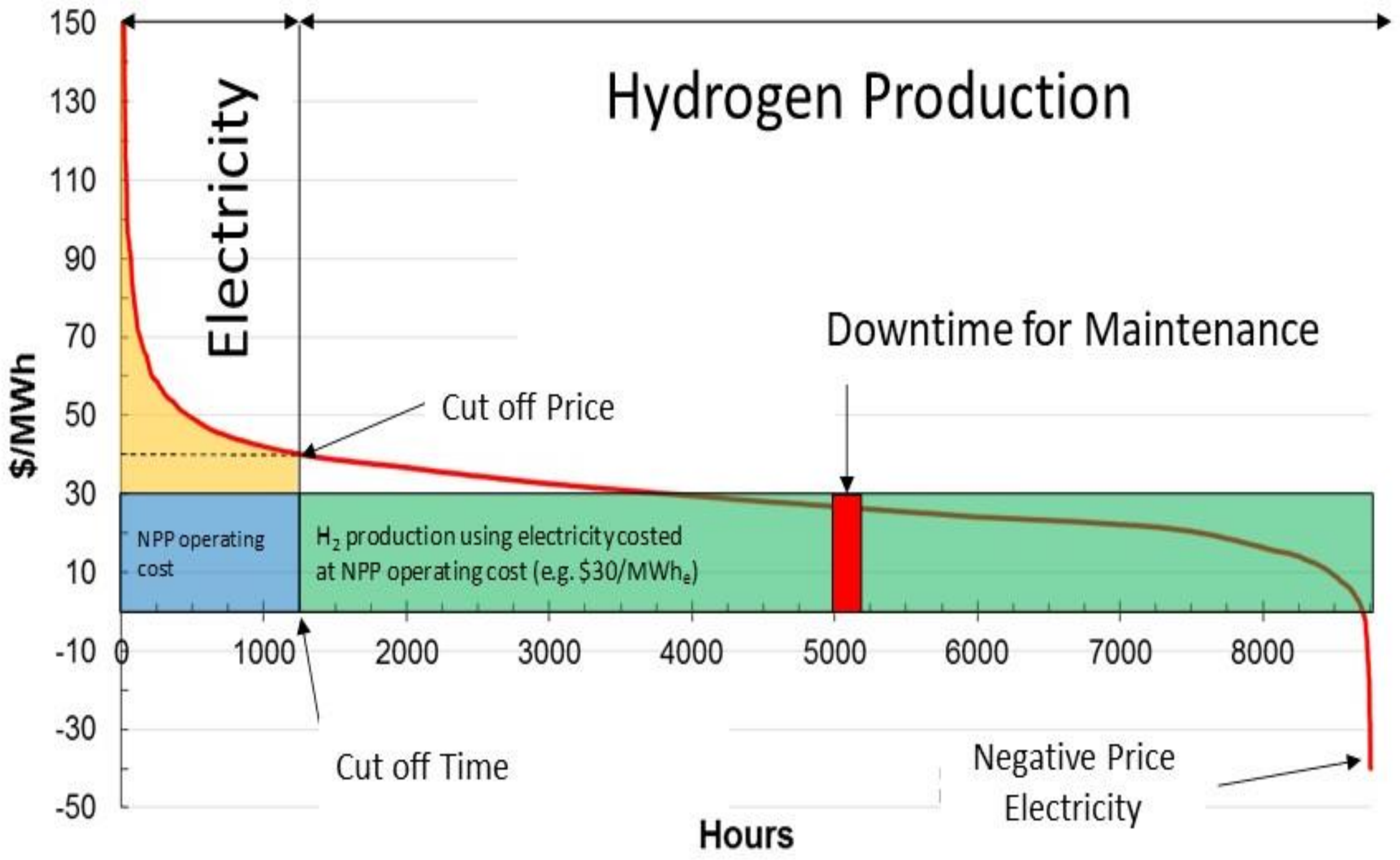
- When very low-price electricity—buy for HTE
  - Grid electricity to hydrogen production (buy electricity)
  - Reactor heat to HTE and low-cost heat storage system
- When very high electricity prices
  - Reactor heat and stored heat to produce electricity
  - No hydrogen production



Nuclear Energy Hydrogen Generation Strategy

Plant Produces H_2 Most of the Time for Economic High H_2 Plant Capacity Factor

- **Hydrogen is storable so do not need continuous production for customer**
- Plant produces two products
  - Hydrogen
  - Electricity
- **Address seasonal variations in electricity demand with base-load reactor and variable hydrogen production**



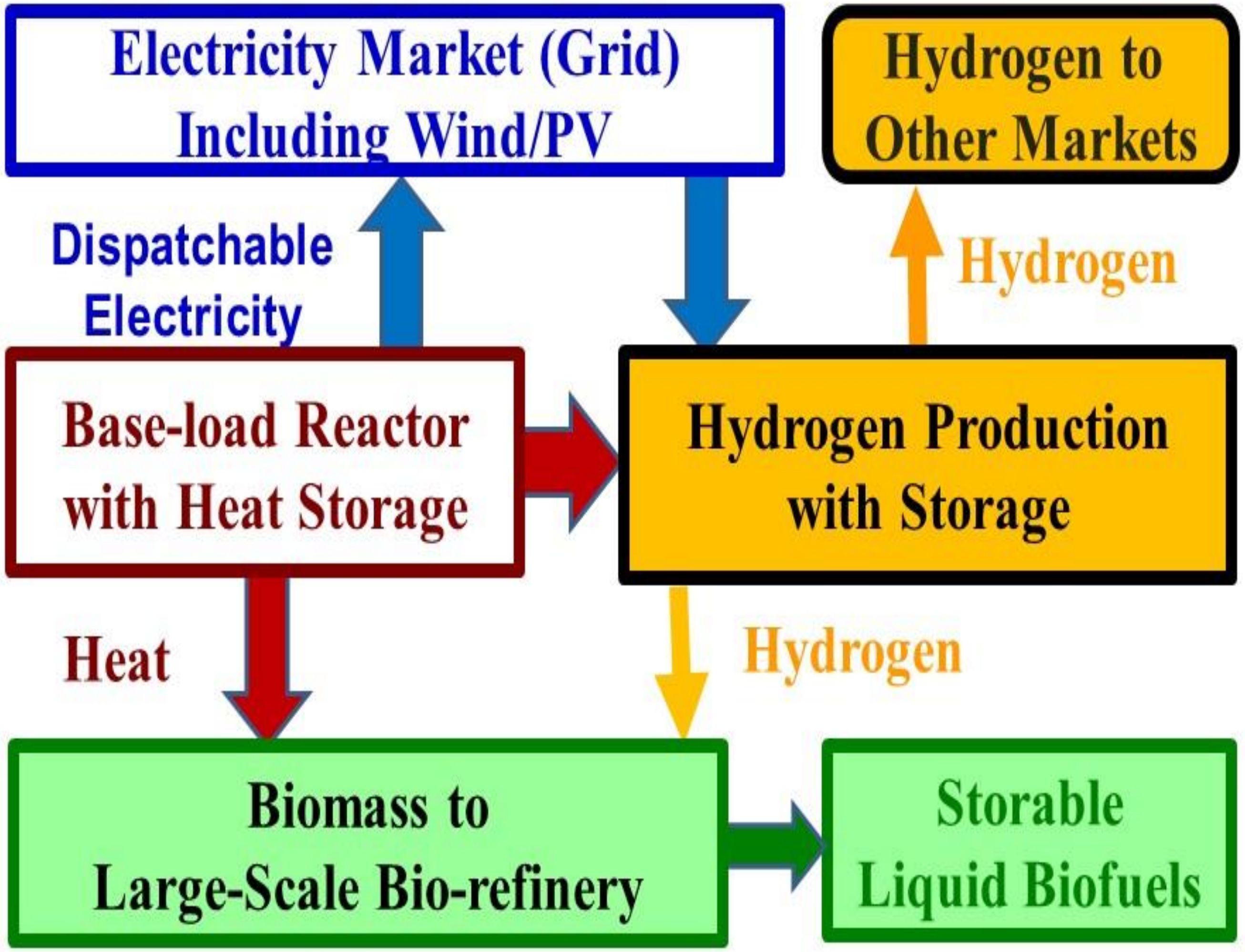
R. Boardman, INL; Evaluation of Non-electric Market Options for a light-water reactor in the Midwest (Light Water Reactor Sustainability Market Study, March 2019

Systems Integration:

Critical Challenges

Large Scale Nuclear Electricity Hydrogen Biofuels System (Wind and Solar Where Economic)

- System produces three products
  - Dispatchable electricity
  - Dispatchable hydrogen
  - Liquid biofuels
- Heat distance transport limits forces co-locate facilities
  - Reactor with heat storage
  - Hydrogen production
  - Biorefineries
- Scale
  - Many gigawatts of nuclear heat
  - 250,000 barrel/day equivalent biorefinery
  - Gigawatt day-to-week heat storage



Characteristics of Different Energy Systems

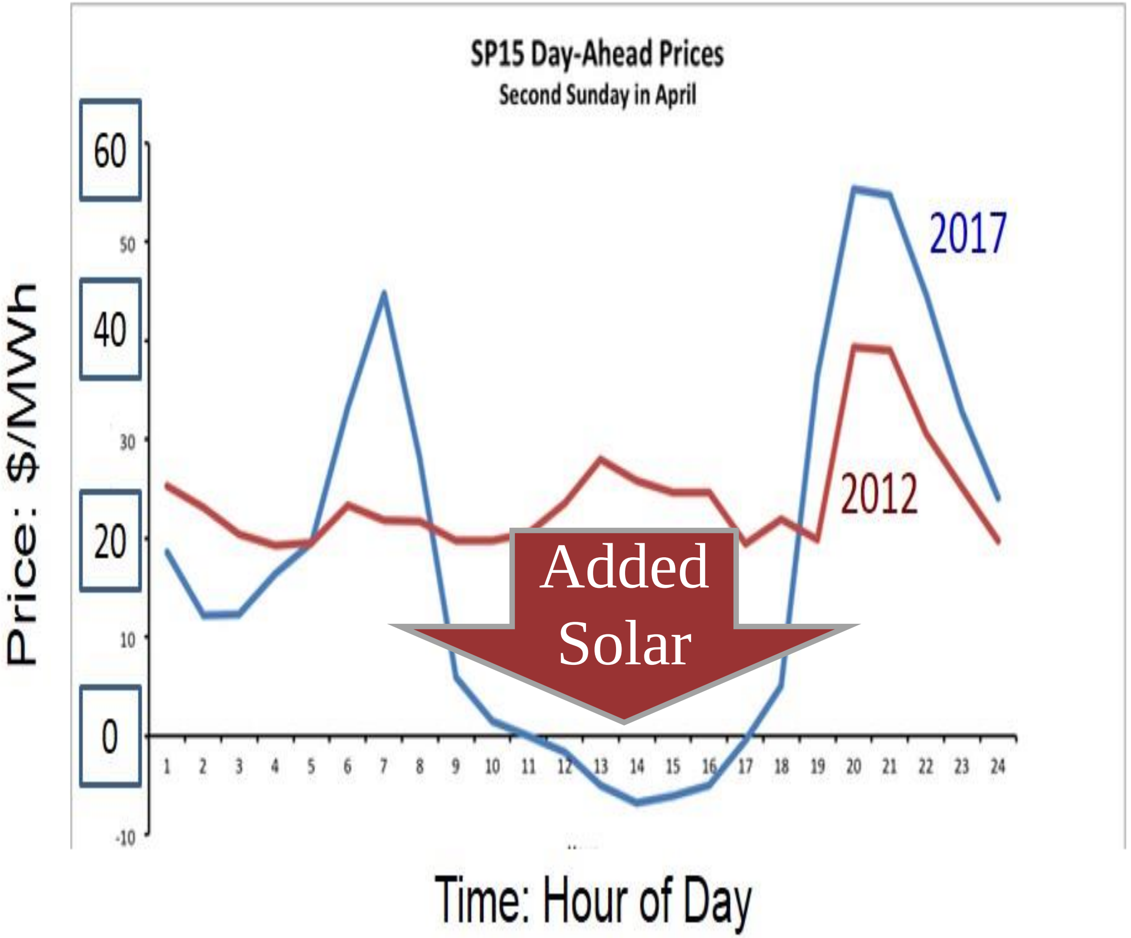
	Electricity	Hydrogen	Biofuels	Heat
Production Costs	**High (Work)**	High (Work)	Medium	Low
Storage Costs	**High**	Low	Very Low	Low
Transport Cost	**High**	Medium	Low	Limited Distance

Differences in Energy Forms Will Drive System Design

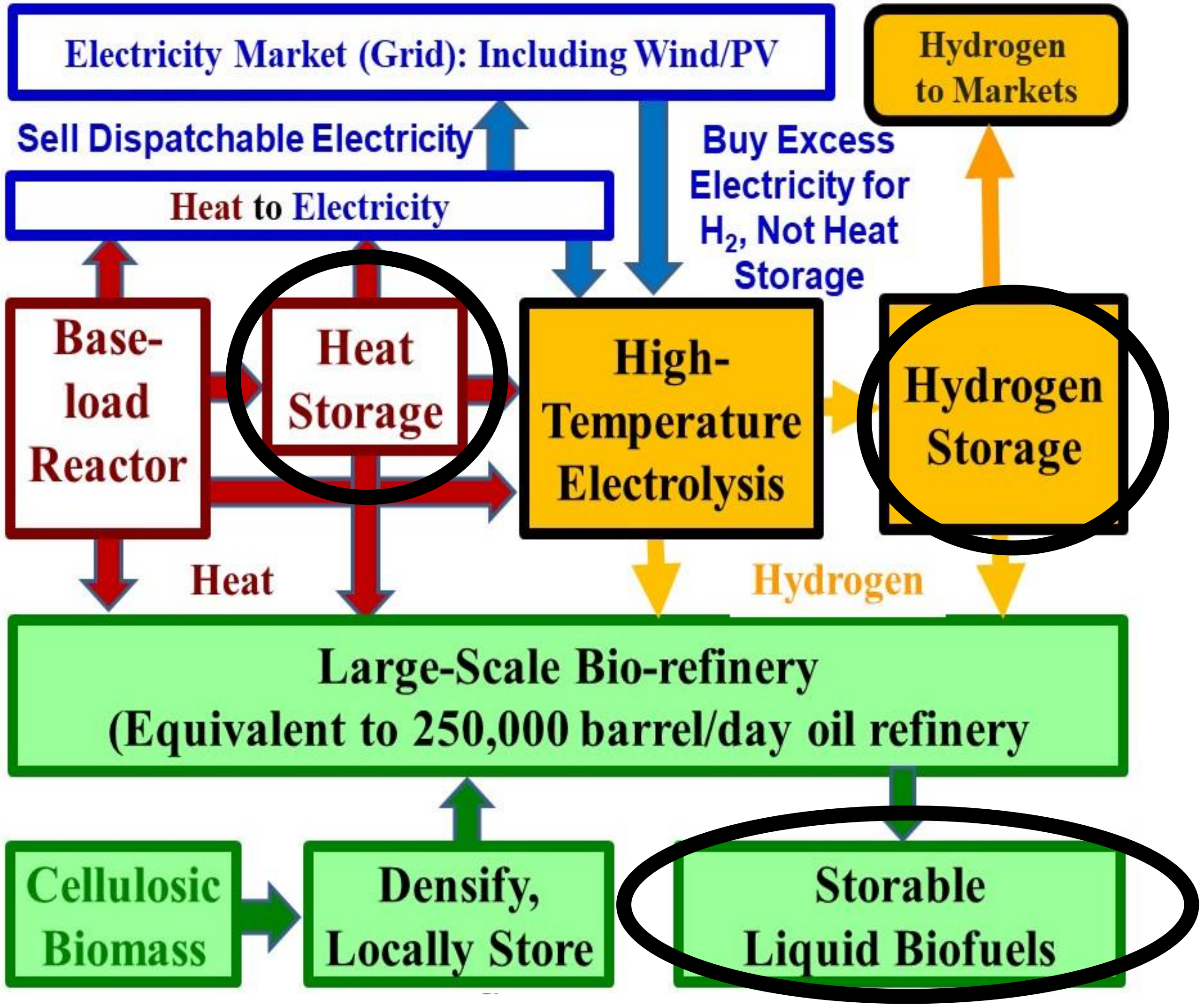
All-Electric Low-Carbon World Is Very Expensive

Role of Wind and Solar PV Dependent Upon Location and Low-Cost Systems for Variable Electricity

- Wind and solar PV economics
  - Low-cost electricity some locations
  - Hourly to seasonal electricity backups (batteries, etc.) expensive
- Total system costs strongly dependent upon systems that provide variable electricity and the capability to buy/use low-price electricity when available
  - Heat storage
  - Hydrogen production
  - Biofuels



Integrated Energy Systems Enables Economic Integration of Wind and Solar

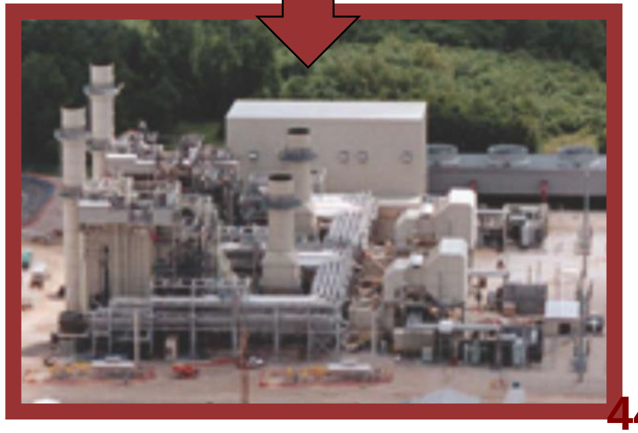


Expensive

Wind / Solar No Heat Generation

Expensive Electric Storage

Backup Gas Turbine when Deplete Storage

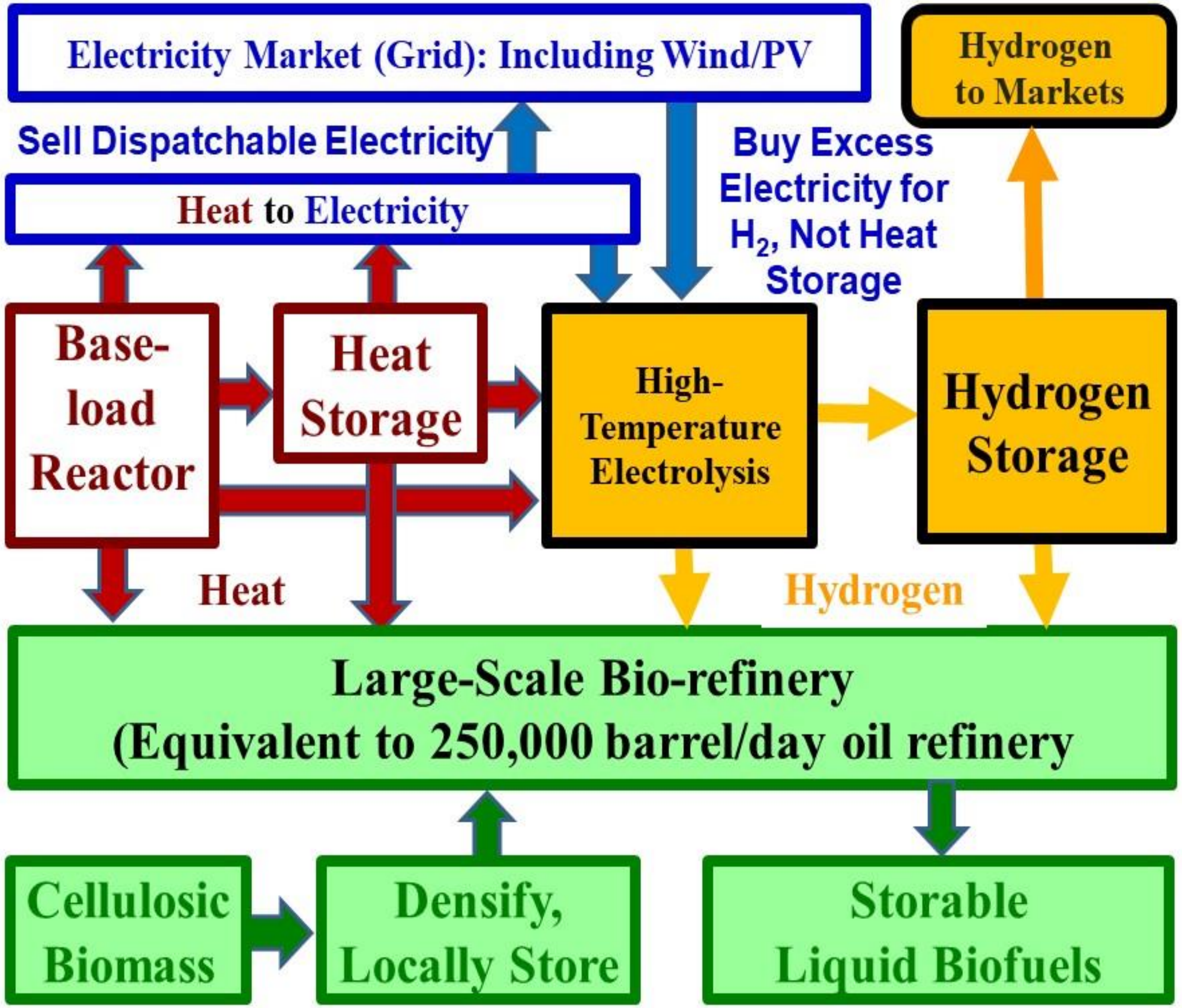


High-Priority Challenges

- Development and deployment of methods to convert cellulosic biomass into high-density, storable, cheap-to-transport intermediate biomass product to enable low-cost large-scale biorefineries
  - Need technology demonstration at scale
  - Chicken and egg deployment challenge: How start up system?
- Mega-scale heat storage coupled to nuclear power plants
- Large-scale biorefinery process development: If good economic case, the major oil companies will quickly develop technology
- Higher-temperature reactors to enable more choices for biorefinery flowsheets (can use existing reactors) than existing light-water reactors

Conclusions

- Potential for faster decarbonization
  - Do not have to massively change existing infrastructure with biofuels
  - Technology challenges are limited compared to most low-carbon alternatives
- Plays to U.S. strengths
- Enables larger-scale use of wind and solar because solve the non-dispatchable challenge of these energy sources



Biography: Charles Forsberg

Dr. Charles Forsberg is a principal research scientist at MIT. His research areas include Fluoride-salt-cooled High-Temperature Reactors (FHRs) and utility-scale heat storage including Firebrick Resistance-Heated Energy Storage (FIRES). He teaches the fuel cycle and nuclear chemical engineering classes. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory.

He is a Fellow of the American Nuclear Society, a Fellow of the American Association for the Advancement of Science, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in waste management, hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design and is a Director of the ANS. Dr. Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. He has been awarded 12 patents and published over 300 papers.

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Heat Storage Coupled to Generation IV Reactors for Variable Electricity from Base-load Reactors: Changing Markets, Technology, Nuclear-Renewables Integration and Synergisms with Solar Thermal Power Systems

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