Gigawatt-Hour Heat Storage with Assured Peak Electric Generating Capacity

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Workshop Proceedings

Heat Storage Coupled To Gen 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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ADVANCED NUCLEAR POWER PROGRAM

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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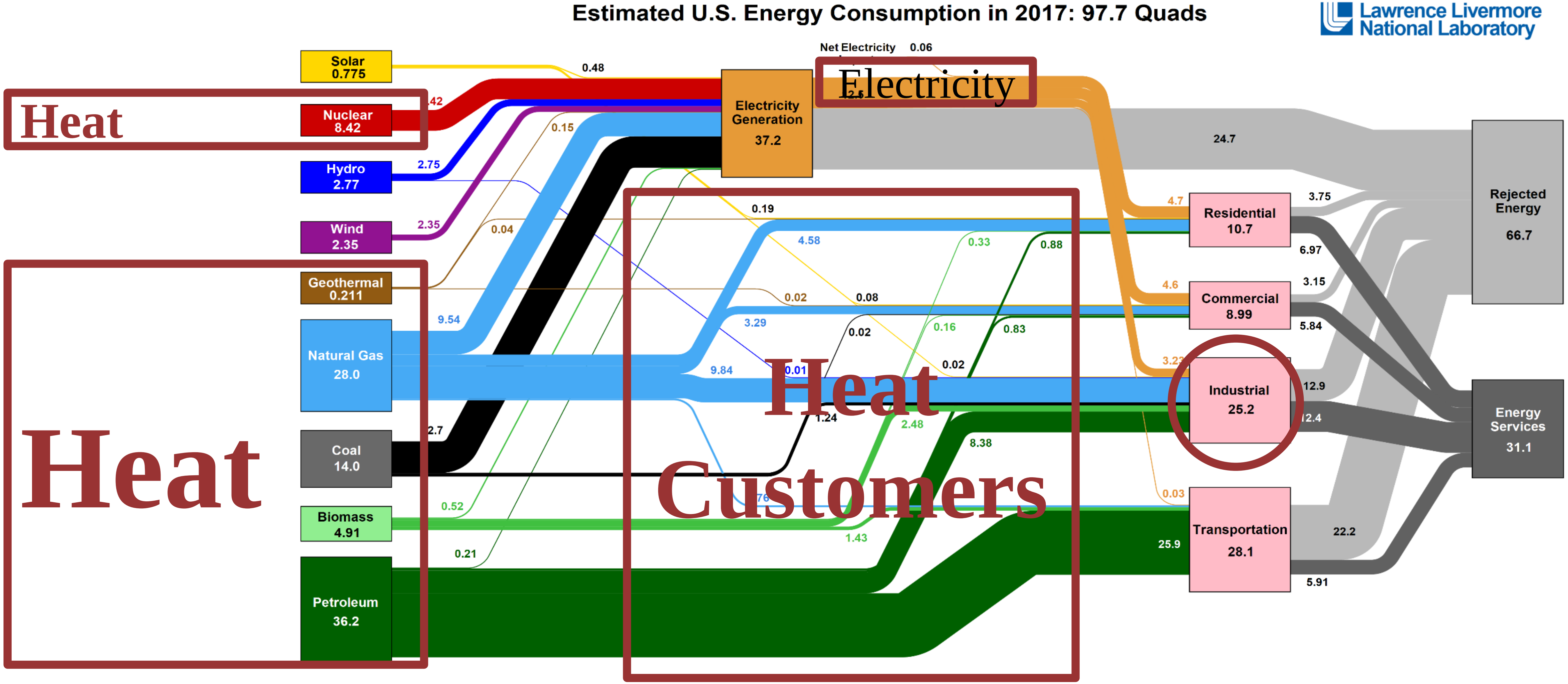
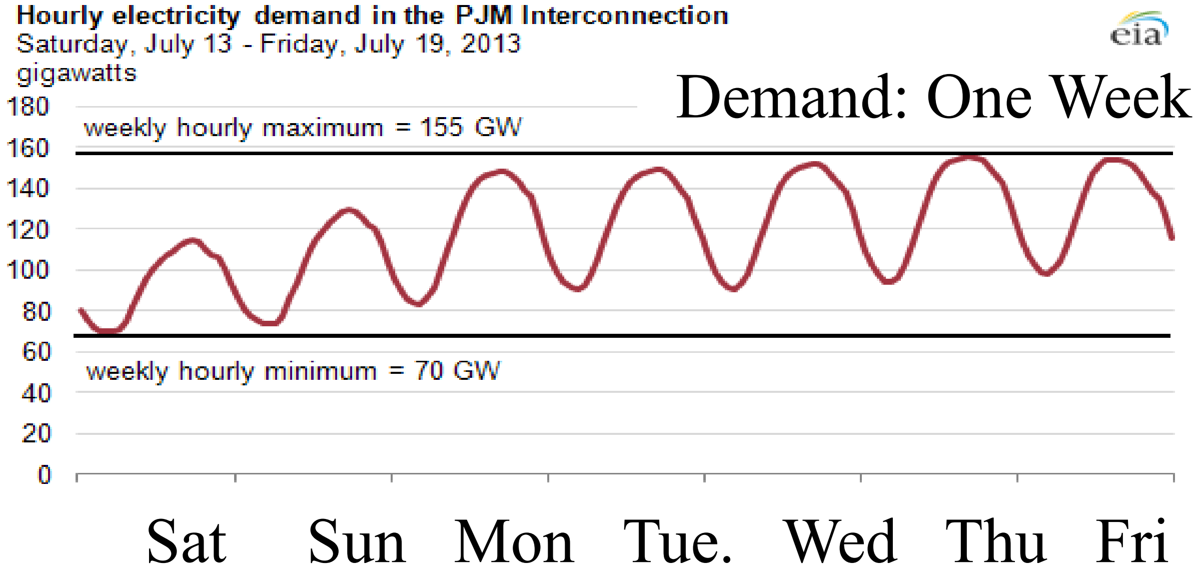
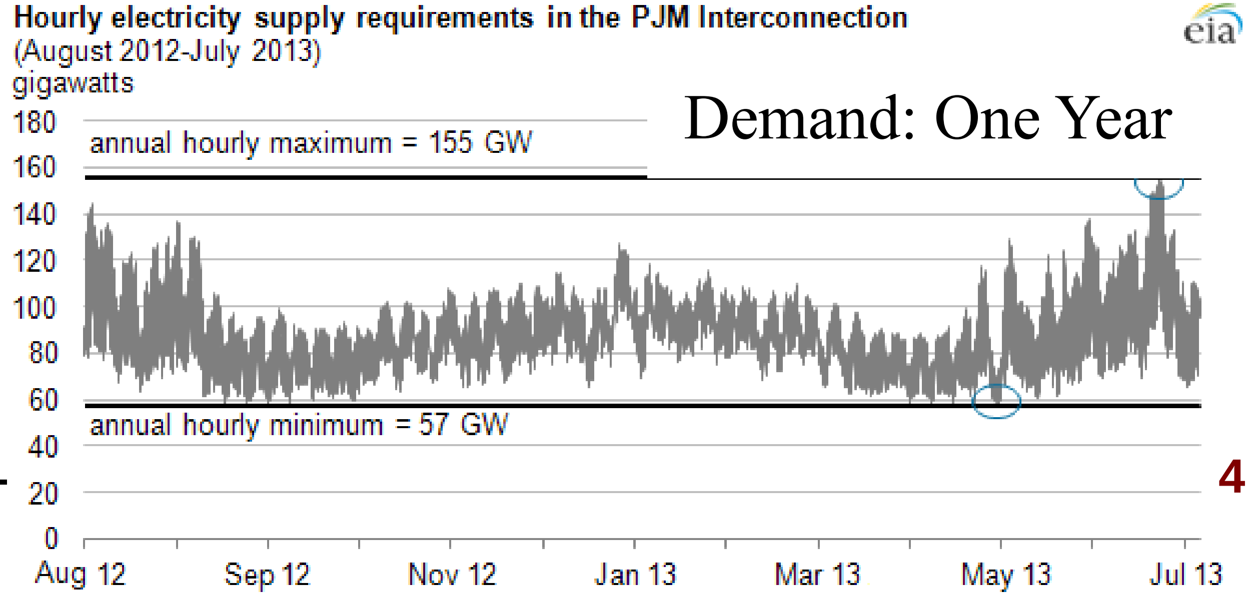
Most Energy Is Generated and Used as Heat



In Low-Carbon System Need Storage to Match Production with Demand: Hourly, Daily, Weekly and Seasonal Storage

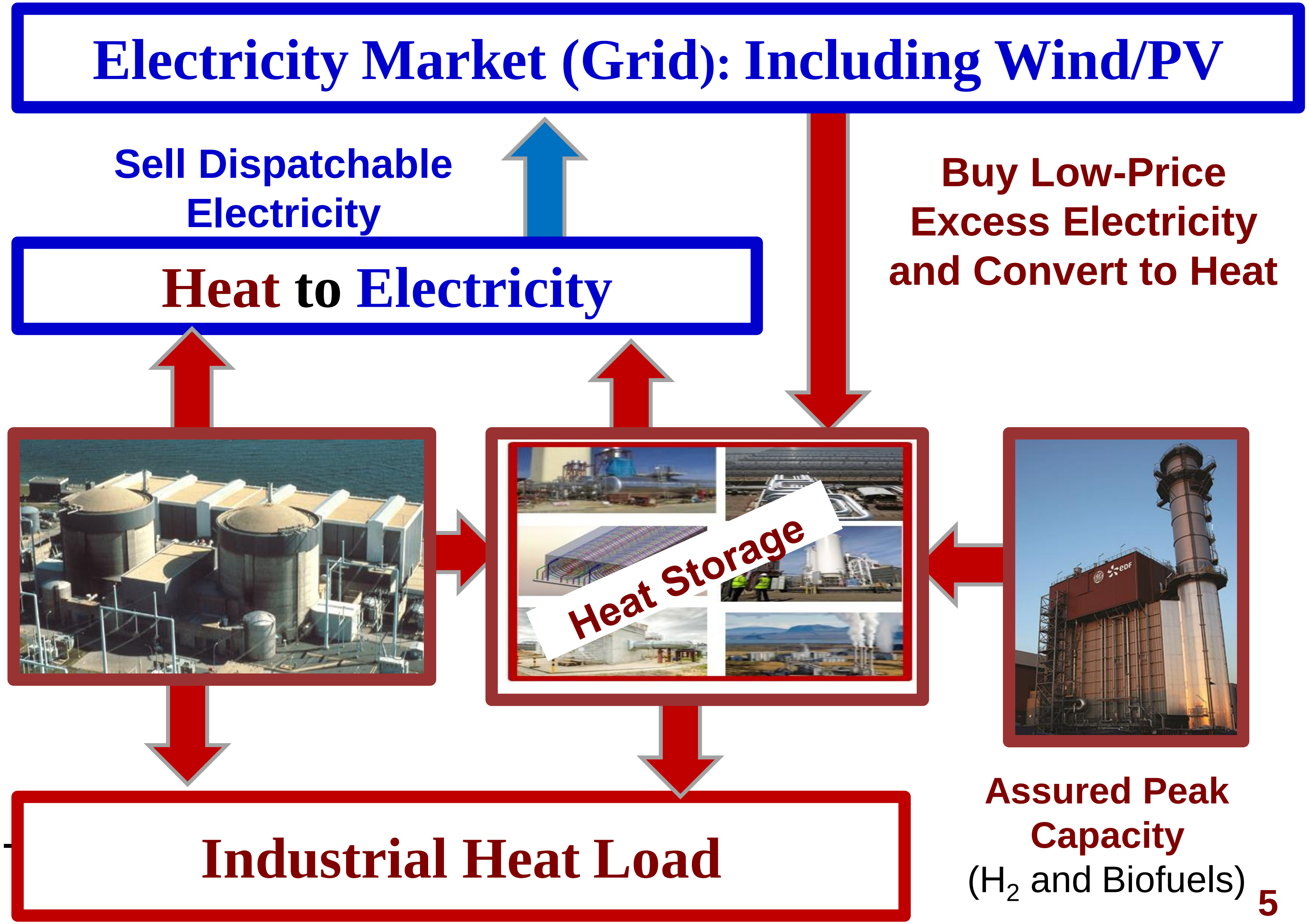
- Low-carbon technologies have high capital costs and low operating costs
  - Nuclear
  - Solar
  - Wind
  - Fossil fuels with CCS
- Must operate near full capacity to minimize costs
- Maximum outputs do not match electricity demand





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 to heat storage (wind/PV)
- 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

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

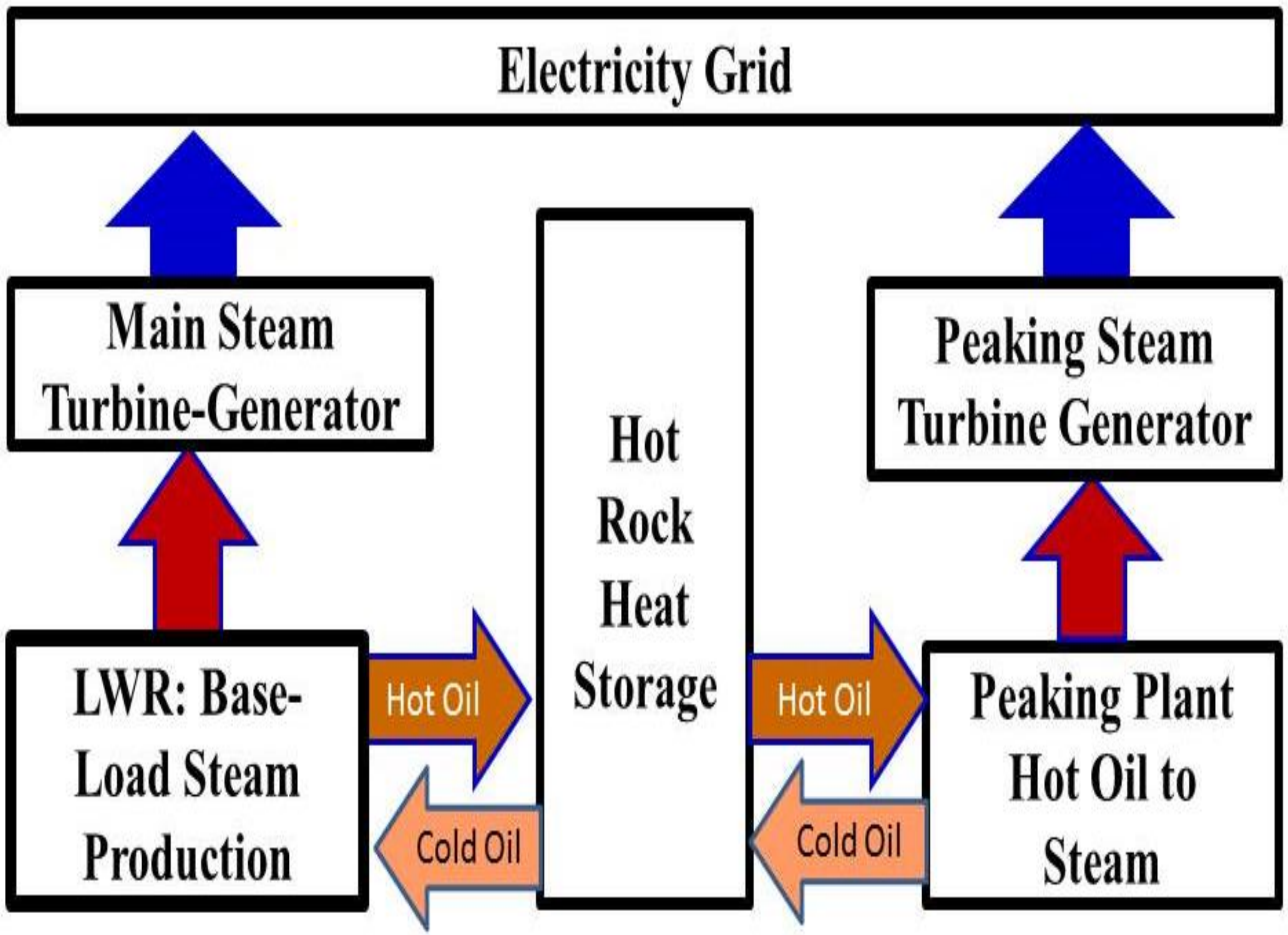
Nitrate Salt Heat Storage Proposed for Sodium, Salt and Helium Cooled Reactors

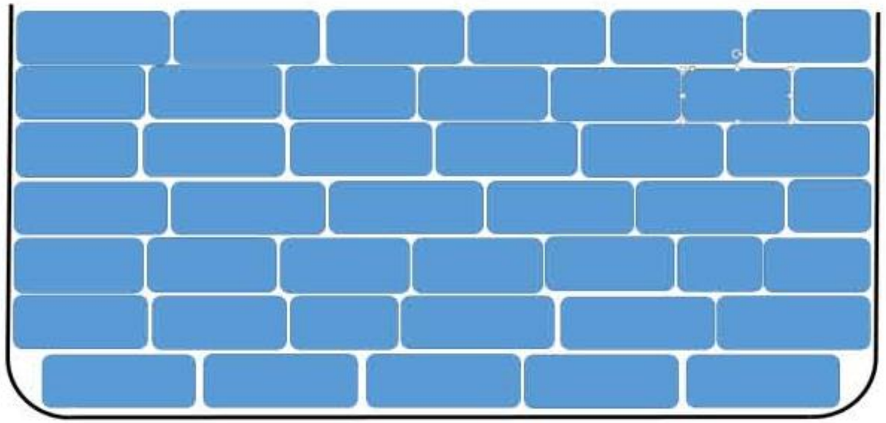
Solana Generating Station (2013, U.S., ~4200 MWh(t))

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

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

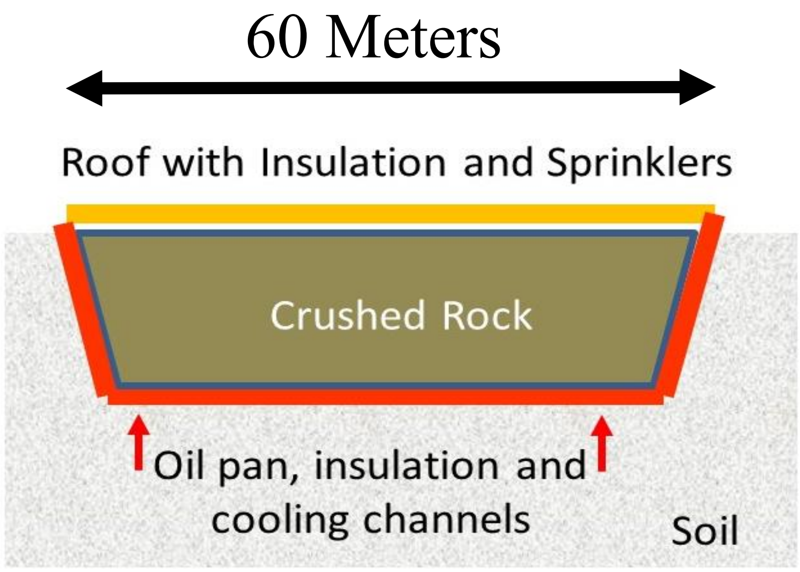


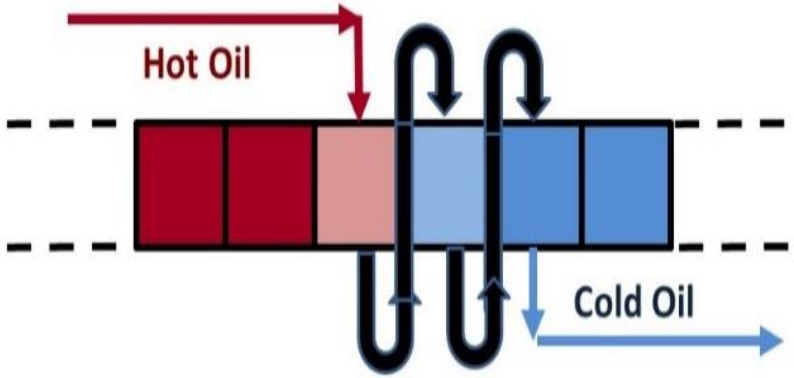


Korean Design: Large barge (60 by 450m) with multiple tanks for 20 GWh(e) heat storage: Supertanker technology

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

- Heat Storage: Single Trench
  - 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

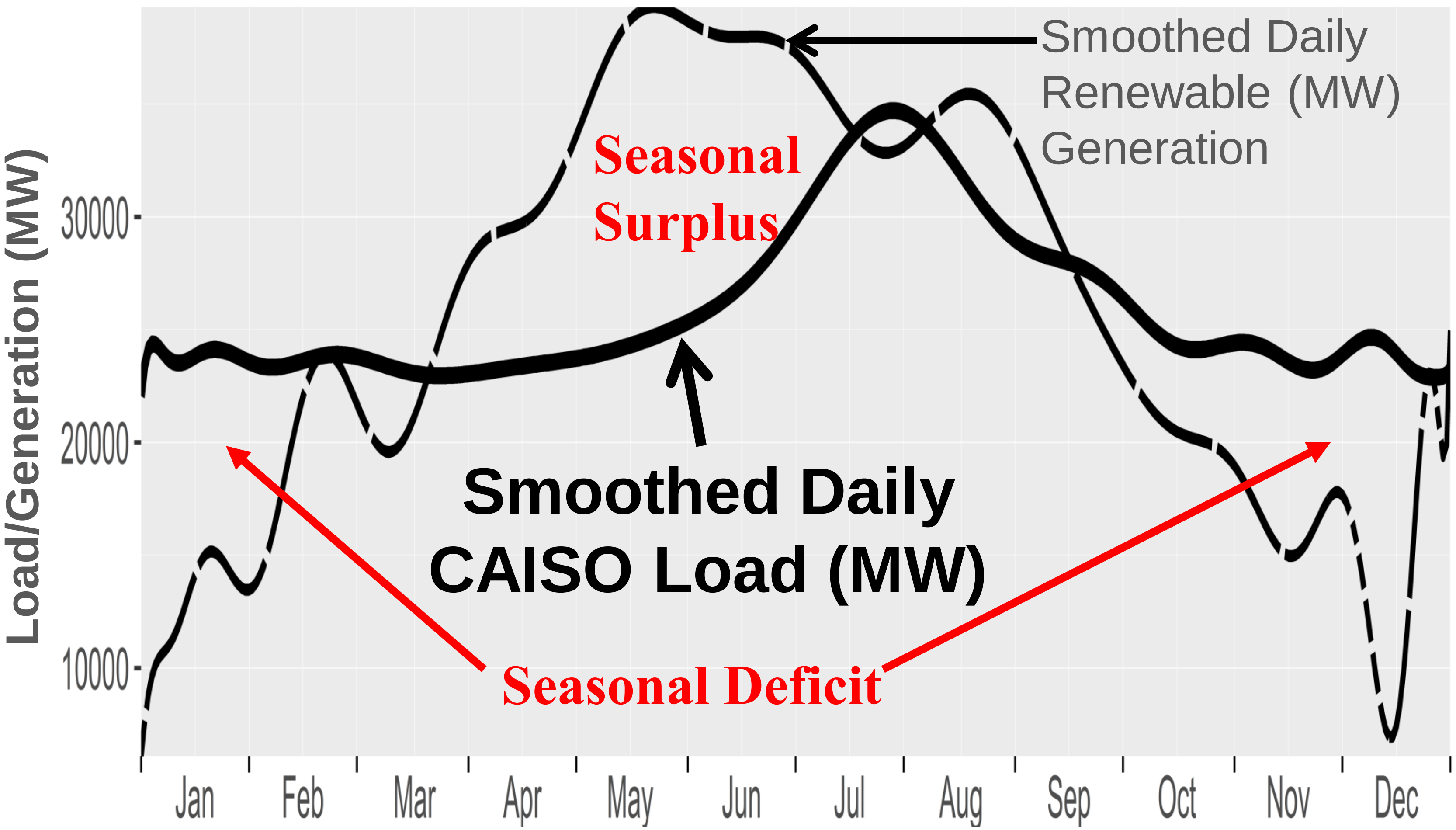




Can We Drive Incremental Heat-Storage Capital Cost Below $1/kWHr?

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



Generating Capacity To Address Seasonal Mismatch
Cheaper with Thermal than Electricity Storage

Electricity Storage


Generation

+

Electricity Storage

+


Backup Gas Turbine for Depleted Storage

Heat Storage

Turbine-Generators Size to Peak Demand

Reactor or CSP

Heat Storage

Low-Cost Peaking Boiler or Furnace

Conclusions

- Energy storage is all about economics
- Match production with demand in a low-carbon world where all technologies have high capital costs and low operating costs
- Sources of variability
  - Demand variations: hour, day, week and seasonal
  - Generation variation: Solar and wind
- Heat storage
  - Potential for costs to be more than an order of magnitude less than electricity storage: Hourly to weekly storage appears viable because of low cost
  - Assured backup capacity with heat storage (furnace) is much cheaper than assured backup capacity with electricity storage (batteries plus gas turbine)
  - Heat storage technology about a decade behind electricity storage technology that was built on electronic, hand tool and then auto markets

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.

References

1. C. W. Forsberg, H. Gougar, and P. Sabharwll, *Heat Storage Coupled to Generation IV Reactors for Variable Electricity from Base-load Reactors: Workshop Proceedings*, ANP-TR-185, Center for Advanced Nuclear Energy, Massachusetts Institute of Technology INL/EXT-19-54909, Idaho National Laboratory, 2019, https://www.osti.gov/biblio/1575201
2. C. W. Forsberg, "Variable and Assured Peak Electricity from Base-Load Light-Water Reactors with Heat Storage and Auxiliary Combustible Fuels", *Nuclear Technology* March 2019. https://doi.org/10.1080/00295450.2018.1518555
3. C. Forsberg and P. Sabharwall, *Heat Storage Options for Sodium, Salt and Helium Cooled Reactors to Enable Variable Electricity to the Grid and Heat to Industry with Base-Load Operations*, ANP-TR-181, Center for Advanced Nuclear Energy, Massachusetts Institute of Technology, INL/EXT-18-51329, Idaho National Laboratory
4. C. Forsberg, Stephen Brick, and Geoffrey Haratyk, "Coupling Heat Storage to Nuclear Reactors for Variable Electricity Output with Base-Load Reactor Operation, *Electricity Journal*, **31**, 23-31, April 2018, https://doi.org/10.1016/j.tej.2018.03.008
5. The Future of Nuclear Energy in a Carbon Constrained World, Massachusetts Institute of Technology, https://energy.mit.edu/wp-content/uploads/2018/09/The-Future-of-Nuclear-Energy-in-a-Carbon-Constrained-World.pdf
6. C. Forsberg, K. Dawson, N. Sepulveda, and M. Corradini, *Implications of Carbon Constraints on (1) the Electricity Generating Mix for the United States, China, France and the United Kingdom and (1) Future Nuclear System Requirements*, MIT-ANP-TR-184 (March 2019)
7. C. W. Forsberg (March 2019): Commentary: Nuclear Energy for Economic Variable Electricity: Replacing the Role of Fossil Fuels, *Nuclear Technology*, **205**, iii-iv, DOI:10.1080/00295450.2018.1523623