LucidCatalyst

ARPA-E FLEXIBLE ADVANCED NUCLEAR STUDY:

OVERVIEW AND RESULTS

Prepared by LucidCatalyst

January 2020

The questions that motivated the study

- What kind of power plant will be needed in the future and why?
- How do we create value for those future customers?
- Is flexibility valuable? How valuable?
- What can advanced reactors cost in these future markets?
- How could this guide your product development?

Commercialization Challenge for New Reactors

Customers hate new technology

- Customers want value, not technology
- Customers buy new technology when the alternative is worse
- Utilities are like other customers, only more so!

- **So, make a great product—that is easy to buy!**

How can we develop low-cost, high performance products?

- **With a clear understanding of the customer's requirements**
  - Make sure you know who the real competition is
  - May include providing something that they didn't know they needed
  - Or meeting their needs in a new way that they didn't anticipate

- **Design to Cost**
  - Flow down cost targets to all subsystems
  - Understand the full costs, and how design decisions drive costs later in the production/delivery/operational phases
  - Iterate when cost targets are missed
  - When iterating, make sure that the functions that are driving cost are needed/valuable/worth it

Letting the market define the requirements

- **Technology agnostic study**
- **Policy agnostic**
- **Investigated requirements for a generic advanced reactor**
- **Key questions for future market conditions-2034**
    - What is the maximum allowable CapEx?
    - What is the value of integrated thermal storage?
    - Are there significant differences between key markets?
    - How do OpEx and fuel costs affect allowable capital cost?

Customers' new plant procurement decision in 2034

- **We assume capacity replacement decisions are starting**
  - Reluctance to invest in long-term carbon emitting assets
  - Storage will be deployed for hourly but not seasonal applications
  - New generating capacity will be needed
  - Continued use of capacity market mechanisms
  - NGCC still sets the marginal power price and the 'expectation' for product value proposition
  - Reluctance to spend more than new NGCC

We modelled four ISO's in 2034

- **Why 2034?**
  - Halfway to 2050
  - Advanced reactors will be ready
  - Most NGCC plants will be nearing retirement age
- **Likely 2034 market characteristics**
  - Low natural gas prices
  - Low cost renewables
  - No major subsidies (ITC, PTC, etc.)
  - Significant/increasing need for flexible, dispatchable resources
  - Economic headwinds for non-flexible baseload generation
  - Coal retirements, older NGCC plants, and relatively low power prices

Scenarios for each ISO

- "Baseline" Renewable vs. High Renewable grid mix
  - First market entrant (1st plant)
  - Projects with co-located thermal storage
  - Alt Scenario #1: $50/tonne CO_2 Price
  - Alt Scenario #2: High penetration scenario (Fleet)
  - Alt Scenario #3: Higher baseline OpEx

Modeling Methodology

PLEXOS Inputs:

- Low/ High RE grid mix (over time) for each ISO and resource operating characteristics

PLEXOS Outputs:

- Hourly and Annual market revenue

- Market energy prices ($/MWh)
- Nuclear Capacity Factors
- Energy Storage Net Generation

Financial Model Inputs:

- Capacity price assumptions, CAPEX recovery period and discount rate, O&M costs, etc.

Financial Model Outputs:

- Maximum Allowable CAPEX

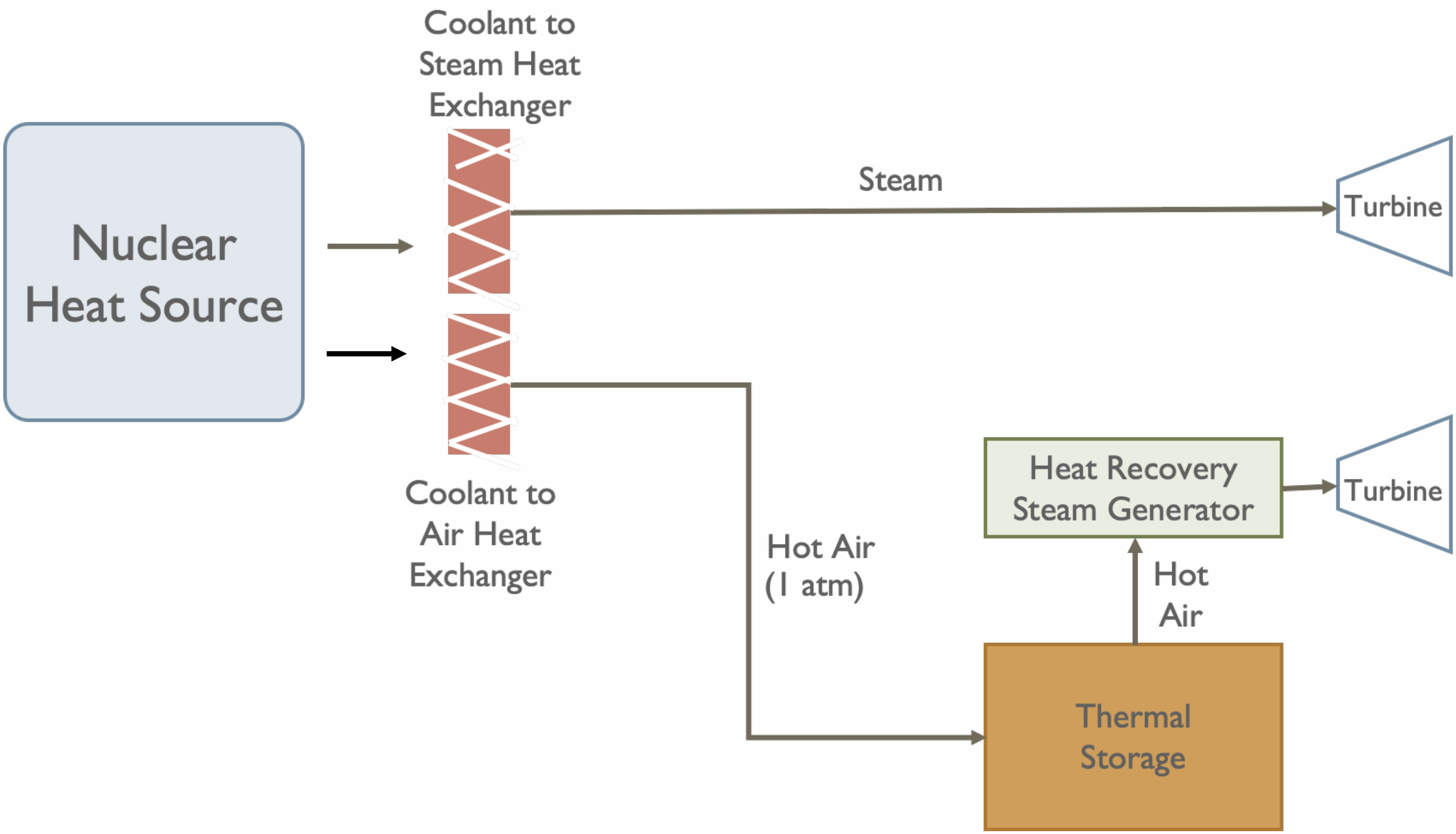
The generic flexible nuclear plant

- 500MWe advanced reactor
- Produces heat at 600-700°C
- 40% thermal efficiency
- Max. Potential Capacity Factor: 92%
- Ramp Rate: 5% of max capacity/min (25MW/min)
- Minimum stable factor: 0%

Idealized thermal energy storage (technology agnostic)

- 500 MW rated output (same as adv. nuclear plant)
- 12 hours of output @ 500 MW (6,000 MWh)
- 90%+ roundtrip net efficiency (mechanical losses, not thermal)
- Outlet temperature: 600-700°C
- Max. state of charge: 100%
- Min. state of charge: 0%

Adv. nuclear and thermal storage configuration



(500MW x 12 hours)

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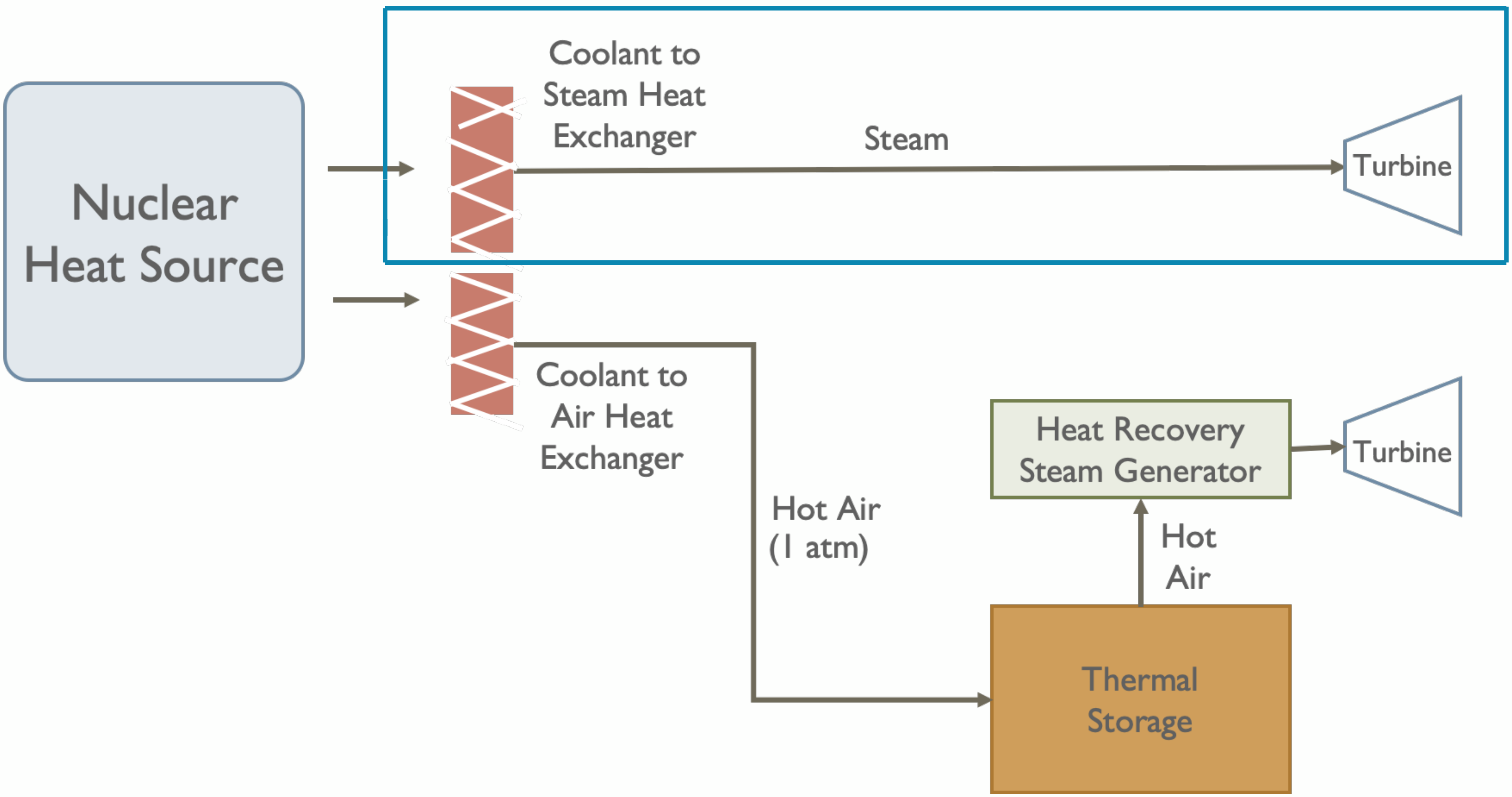
Non-nuclear estimate ~$750/kW (w/o ESS)



(500MW x 12 hours)

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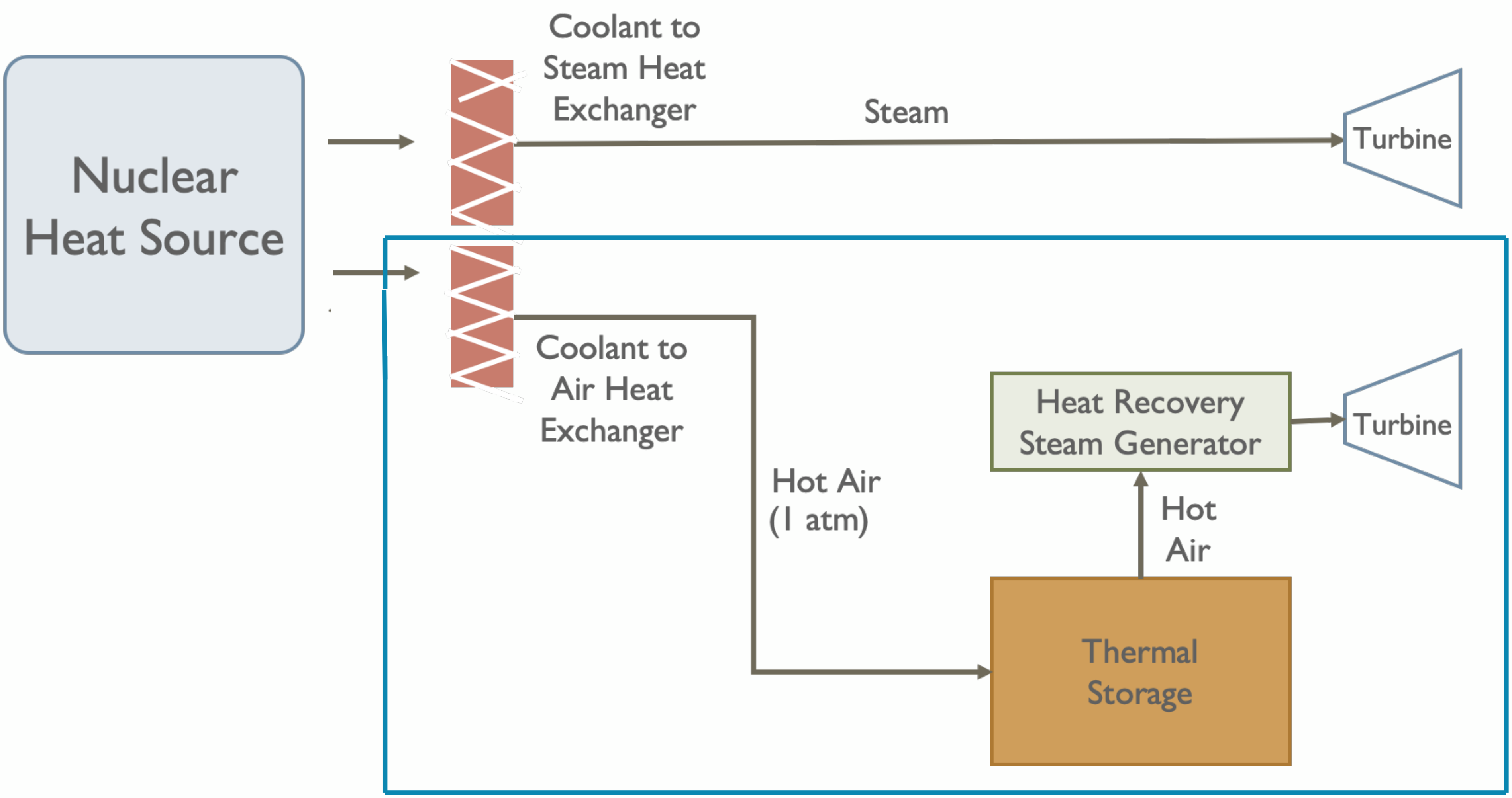
ESS estimate <1,000/kW, $100/kWh



(500MW x 12 hours)

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Results: allowable CapEx is scenario-specific

		Low RE		High RE	
		W/out ESS	W/ ESS	W/out ESS	W/ ESS
ISO-NE	Low capacity price case:	$2,289	$2,962	$1,965	$2,788
	Mid capacity price case:	$2,566	$3,515	$2,242	$3,341
	High capacity price case:	$2,843	$4,068	$2,519	$3,894
PJM	Low capacity price case:	$2,358	$2,988	$2,186	$3,038
	Mid capacity price case:	$2,634	$3,541	$2,462	$3,591
	High capacity price case:	$2,911	$4,095	$2,739	$4,144
MISO	Low capacity price case:	$2,244	$2,857	$2,000	$2,654
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	High capacity price case:	$2,797	$3,963	$2,553	$3,760
CAISO	Low capacity price case:	$2,187	$3,397	$1,968	$3,306
	Mid capacity price case:	$2,464	$3,950	$2,244	$3,859
	High capacity price case:	$2,740	$4,503	$2,521	$4,412

Results: Implications

		Low RE		High RE	
		W/out ESS	W/ ESS	W/out ESS	W/ ESS
ISO-NE	Low capacity price case:	$2,289	$2,962	$1,965	$2,788
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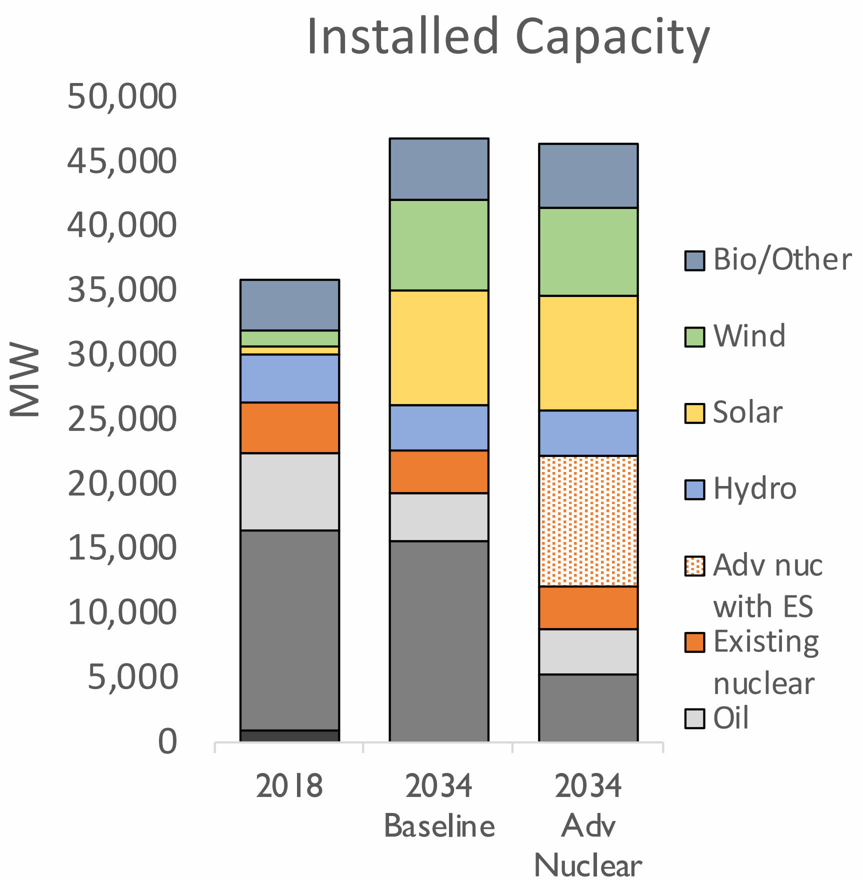
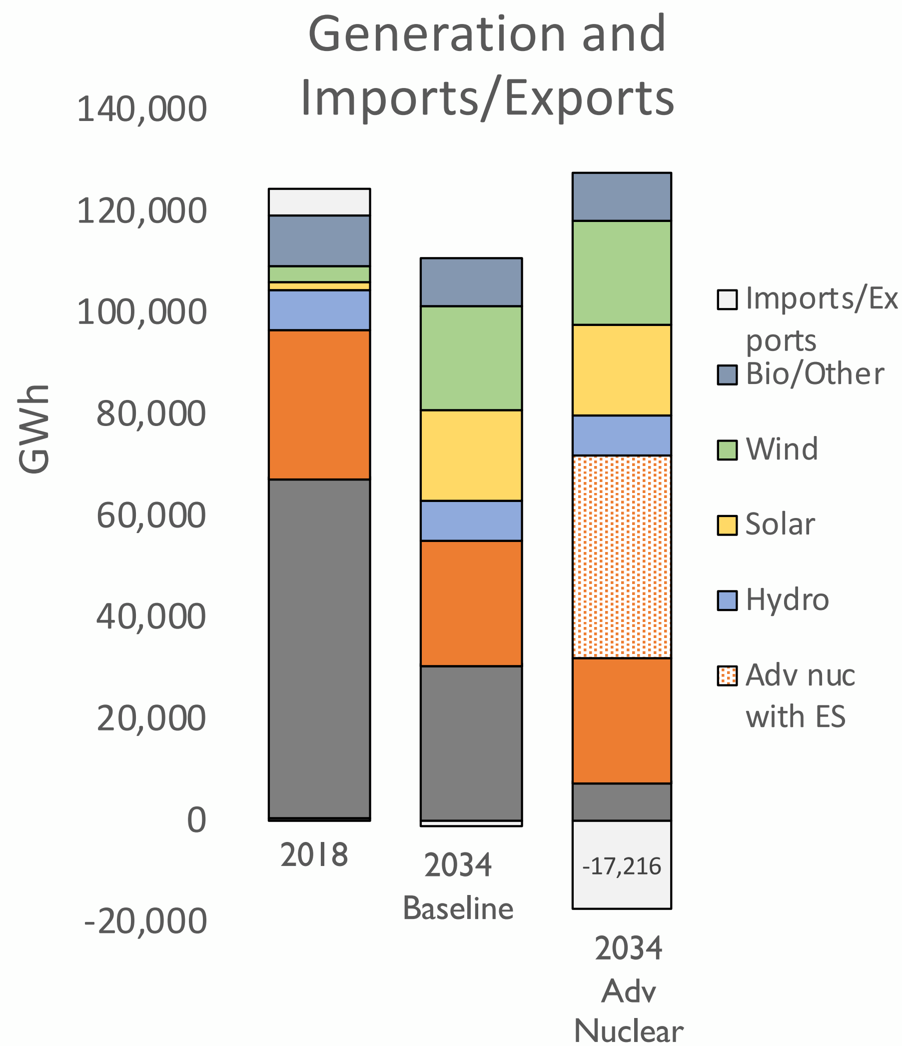
- Companies must aim for <$3,000/kW for their adv. nuclear plants
- Thermal storage enables higher allowable CAPEX; it doubles capacity payments
- But a portion will be necessary to pay for the storage system.
- Capacity price is critically important
  - A "mid" capacity price of $75/kW-year allows for:
    - ~$2,500/kW CAPEX without storage
    - ~$3,500/kW CAPEX with storage
- If on the margin, fuel price and OpEx will be very important

Example: Results for ISO-NE (w/ thermal storage)

- *Overall generation increases in the Advanced Nuclear scenario enabling clean energy exports.*





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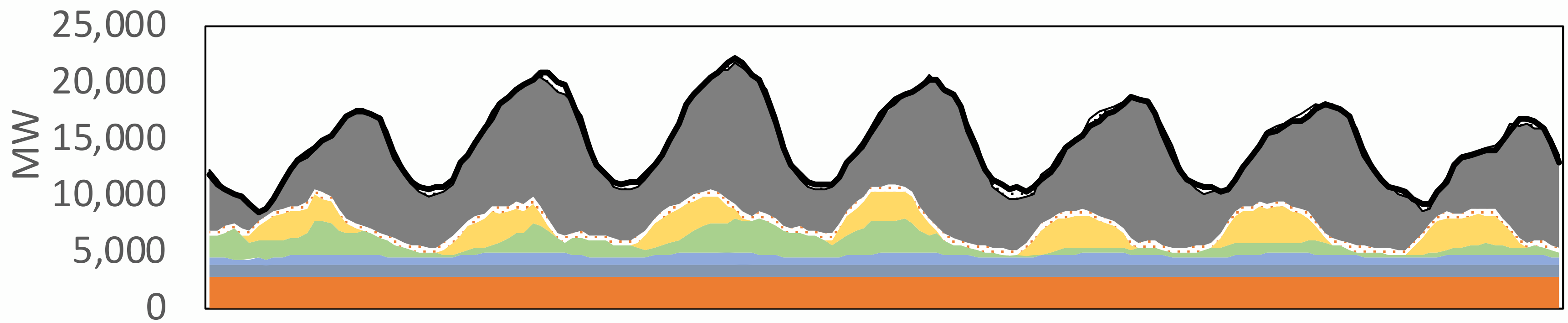
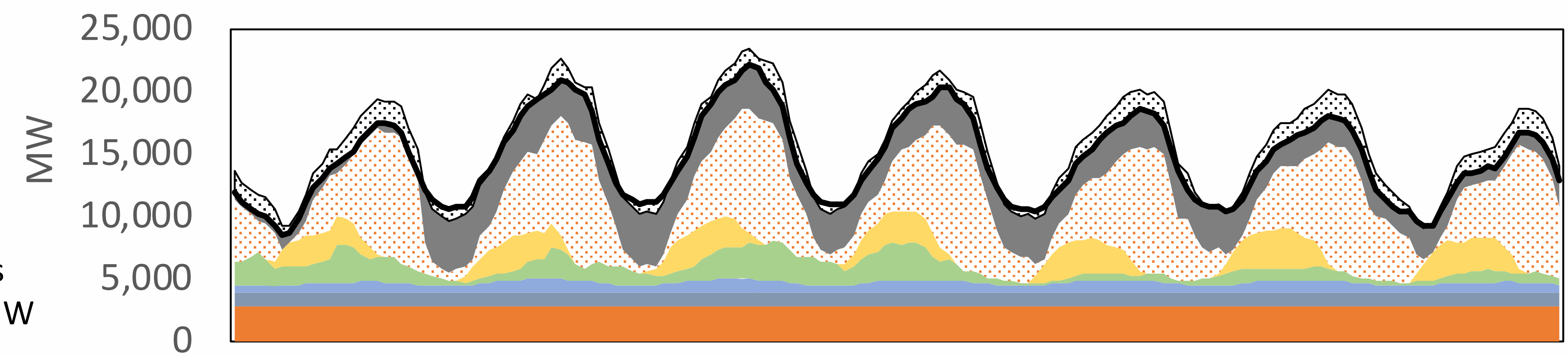
Dispatch in mid July (during seasonal solar peak)

- Flexible advanced nuclear, when coupled with storage, can provide the same grid flexibility as CCGTs

1 Plant (500 MW average 1GW peak)



10 Plants (5,000 MW average 10GW Peak)



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Alt Scenario #1: CO_2 Price

- As expected, establishing a CO2 price dramatically improves the maximum allowable CAPEX requirements:

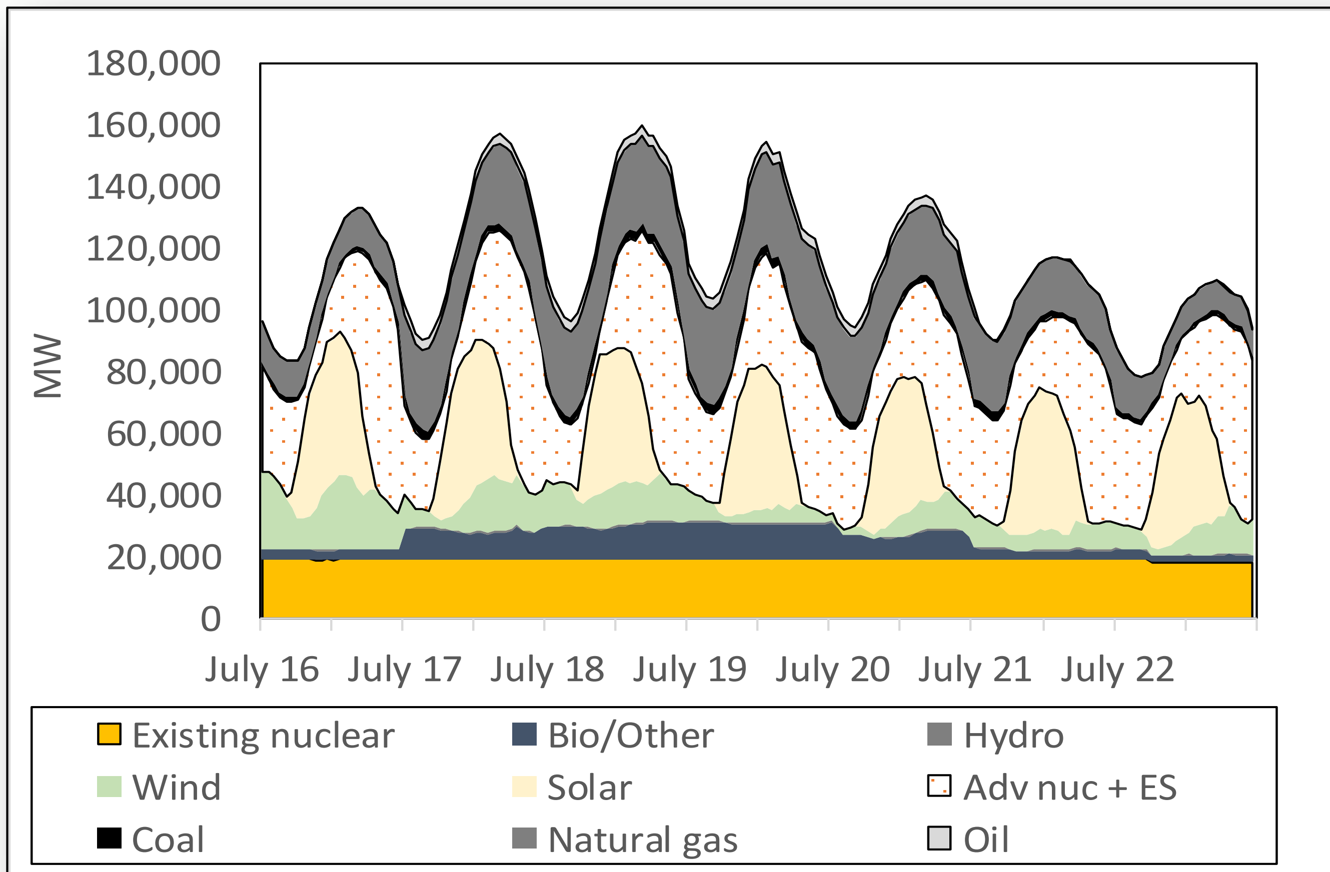
ISO: PJM
Load Zone: PEPCO
Scenario: High RE

CO_2 Price ($/tonne)	Change to Max. Allowable CAPEX (+/-)	
	Without Thermal ESS	With Thermal ESS
$25	+ $947/kW	+ $993/kW
$50	+ $1,889/kW	+ $2,005/kW
$75	+ $2,814/kW	+ $3,017/kW

Alt Scenario #2: Effect of large fleet

- Supply 2/3 of firm generation in PJM with flexible nuclear plants (and co-located thermal storage) dropped the maximum allowable CAPEX by ~$500/kW (from the 1st plant to last plant).

- Total cost of serving PJM's load decreases slightly.
- Average annual energy prices dropped by $4.36/MWh



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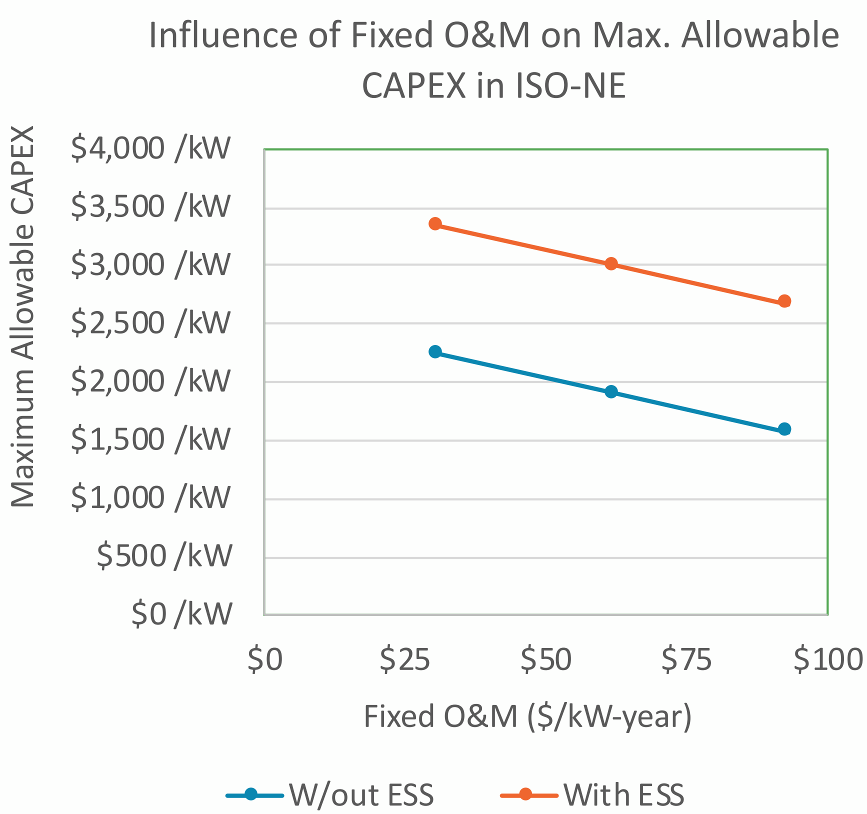
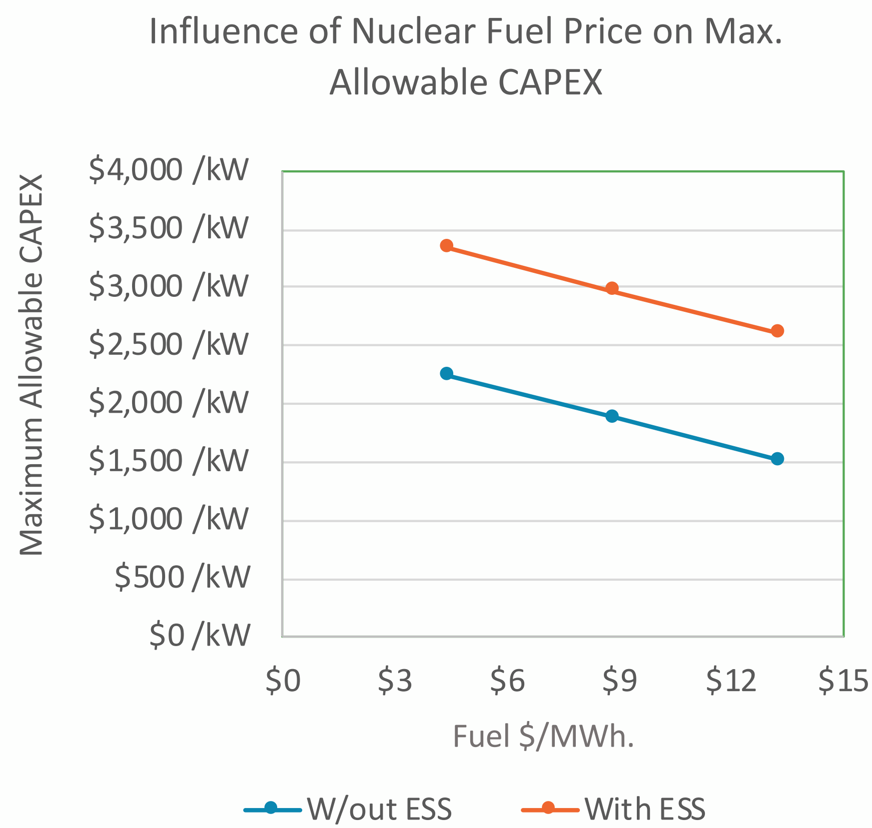
Alt Scenario #3: Alternative O&M, Fuel assumptions

- Increasing the fixed O&M assumptions from $31/kW to $61/kW reduces the maximum allowable CAPEX by $377/kW
- Raising fuel cost from $4/MWh to $12/MWh reduces allowable CAPEX by ~$750/kW





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Value of thermal storage

- Across ISOs modeled, co-locating storage makes economic sense, on average, for less than $1,126/kW
  - Lowest CAPEX Threshold (Low RE - MISO): $613/kW
  - Highest CAPEX Threshold (High RE - CAISO): $1,891/kW

- Without storage, a plant's CF suffers in high VRE zones
  - In the High RE scenario, capacity factors for nuclear plants in southern California drop to 67%.

- These plants are being designed to operate for a minimum of 40 years → it is worth considering what market conditions (particularly VRE penetration) will exist beyond 2034

Conclusions (1 of 2)

- Having a highly-rampable reactor (without storage) may be good for the grid but it does not necessarily benefit a plant's bottom line
  - No value for flexibility
  - Nuclear plants inherently want to run at their maximum rated output
  - Making flexibility economic will require either thermal energy storage, or major market reforms
  - Thermal storage is beneficial for the plant owner at a cost of less than $1,126/kW
  - DTs need to be designing for low CapEx against a validated cost model
  - CapEx goal should be <$3,000

Conclusions (2 of 2)

- Fuel cost and fixed O&M expenses are material considerations – as these decrease, max. allowable CapEx
  - We need to be designing for fuel cycles that are lower in cost than LWR's
- Consider regulated markets as a place to deploy the first unit (insulated from power market volatility/ uncertainty)
  - Early units will need to have a higher expected rate of return to attract customers-Best opportunities
  - Increasing or decreasing the WACC by a percentage point changes the maximum allowable CapEx by ~8-9%
- Developers may want to subtract the costs of known non-nuclear components to better understand the cost constraints of the heat source

Benefits of this study

- We now have clear cost and performance targets for Design Teams
- Grid operators do not know that these products are coming
- These products are not being modeled into future energy systems

Appendix Slides

We need to think very clearly about this

We may find ourselves wanting to believe things like this:

- There will always be a certain percentage of nuclear on the grid
- Nuclear energy's benefits mean that people will want it
- The grid can't function without nuclear
- Nuclear energy is inherently better than other kinds of power generation

- This kind of thinking distracts us from the actual challenge of developing a compelling value proposition

Modeling Assumptions (select)

PLEXOS Assumptions

- Four modeling regions
  - ISO-NE
  - PJM
  - MISO
  - CAISO
- Low/ High RE mix
- Modeling Year: 2034
- 2019 constant dollars
- No CO_2 price
- Co-located Thermal Storage

Financial Assumptions

- 7% WACC
- 22-year CAPEX recovery period
- $50, $75, and $100/kW-yr capacity payment sensitivities
- $4.44/kWh fuel expenditures
- $31/kW-yr fixed O&M
- 12-hour thermal storage receives capacity payment

Expected Future Revenue Sources

- New market mechanisms to reward flexibility are too nascent
- Operating reserve markets will likely expand but more participants will keep prices (revenue) stable
- Energy and Capacity payments = primary revenue sources

Modeling methodology (cont.)

PLEXOS Model Inputs

- Low RE/ High RE resource mix for each ISO
- Flexible adv. nuclear plant inputs: capacity. heat rate, outage schedule (O&M and CAPEX excluded)
- Thermal storage inputs: power rating (MW), capacity (MWh), charging/ discharging efficiencies
- Fossil plant retirement schedule (for select scenarios). Units are assumed to be replaced by adv. flexible nuclear plants.
- Adjustments to PLEXOS built-in fuel price (and CO_2 price inputs for select scenarios)
- Other PLEXOS built-in inputs: Solar PV and Wind resource output profiles, Transmission, etc.

PLEXOS® Power Market Software

PLEXOS Results

- Hourly and Annual market energy prices for "Low RE" and "High RE" scenarios
- Reductions in CO_2 emissions

- Market energy prices ($/MWh)
- Nuclear production and capacity factors
- Energy storage system net generation

Financial Model Inputs

- Capacity price assumptions ($/kW-year)
- CAPEX recovery period (years)
- CAPEX recovery discount rate (%)
- Fuel, variable, and fixed O&M costs for flexible adv. nuclear plants
- Currently available cost estimates for adv. nuclear plant components

Financial Results

- Maximum allowable CAPEX ($/kW) for adv. nuclear plants
- Comparison with current cost component estimates

Post-PLEXOS Financial Model

Plexos Input/Output categories

PLEXOS Inputs & Results	
Inputs	
Plant capacities	Plant capacities are inputs to PLEXOS (with adjustments by LC team for baseline scenario calibration and flexible advanced nuclear additions); summed by plant type (natural gas, solar, wind, etc.) for regional total.
Demand (load)	Demand in each service territory is an input to PLEXOS; summed across service territories for regional total.
Results	
Plant operational dispatch	PLEXOS determines the optimal combinations of plant production across the grid, including output from the advanced nuclear plants, to meet demand in each hour of the modeling period; hourly dispatch is summed over year to calculate total generation by plant in 2034.
Market price	PLEXOS calculates market price in each hour of the modeling period in each service territory based on the marginal costs of the marginal producer to meet demand; market prices are averaged across service territories and hours in year to calculate average market price in 2034.
CO_2 emissions	PLEXOS uses plant operational dispatch, fuel consumption per MWh, and CO_2 emission rate per unit of fuel consumption to calculate CO_2 emissions from plant operation; results are summed across plants and hours in year to calculate total CO_2 emissions in each region in 2034.
Advanced nuclear operational dispatch	This is part of the broader plant dispatch results by hour described above.
Energy storage charging and discharging	PLEXOS optimizes the charging and discharging by hour for each energy storage system in the modeled region, subject to the constraint limiting their hourly charging amount to the coupled nuclear plant's production in the same hour.

Results

		Low RE		High RE	
		W/out ESS	W/ ESS	W/out ESS	W/ ESS
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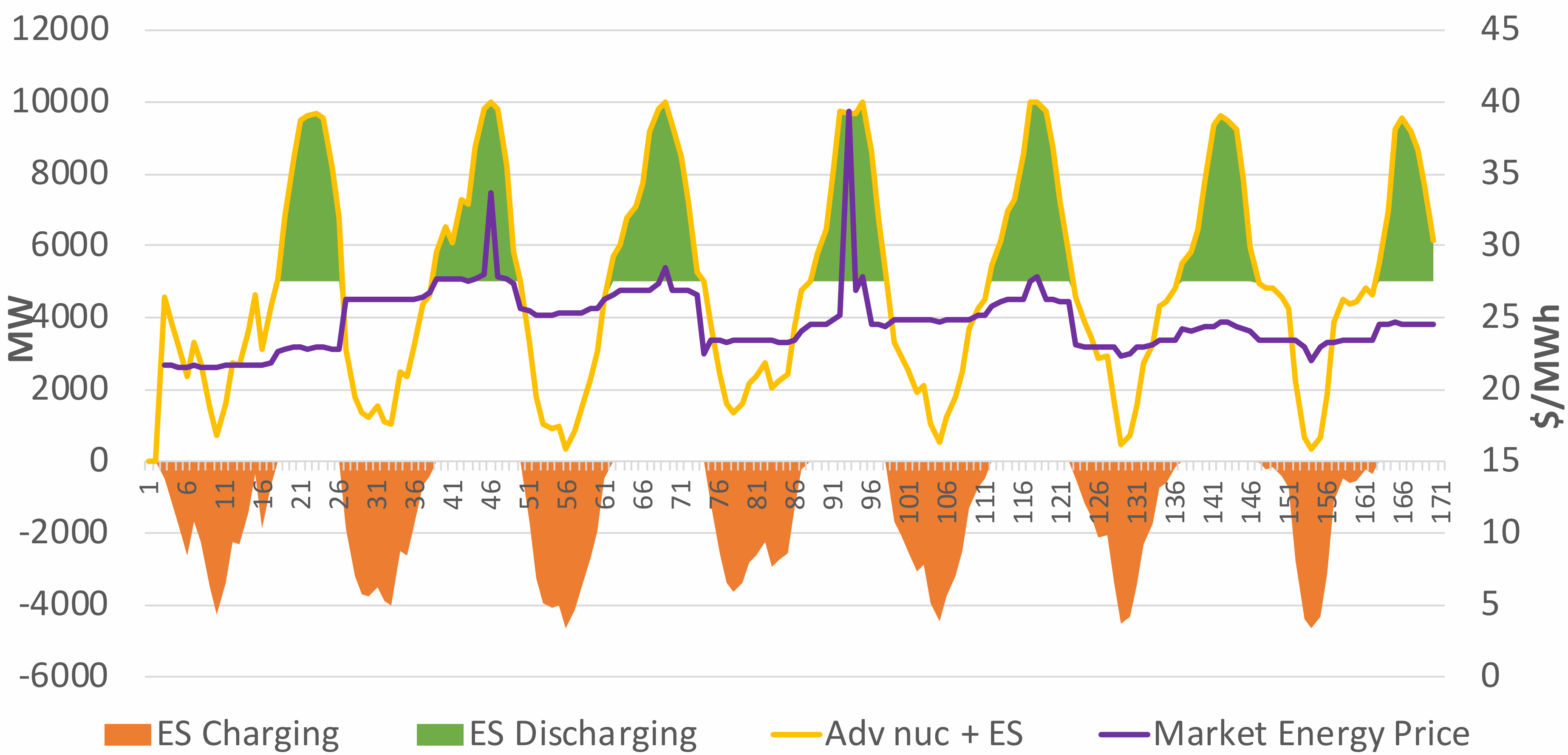
Thermal storage charge/dischar

NOT SURE WHAT THIS REALLY ADDS… JUST SHOWS THAT STORAGE WAS MODELED CORRECTLY…

- The thermal storage system optimizes charging to take advantage of the highest available prices in the market



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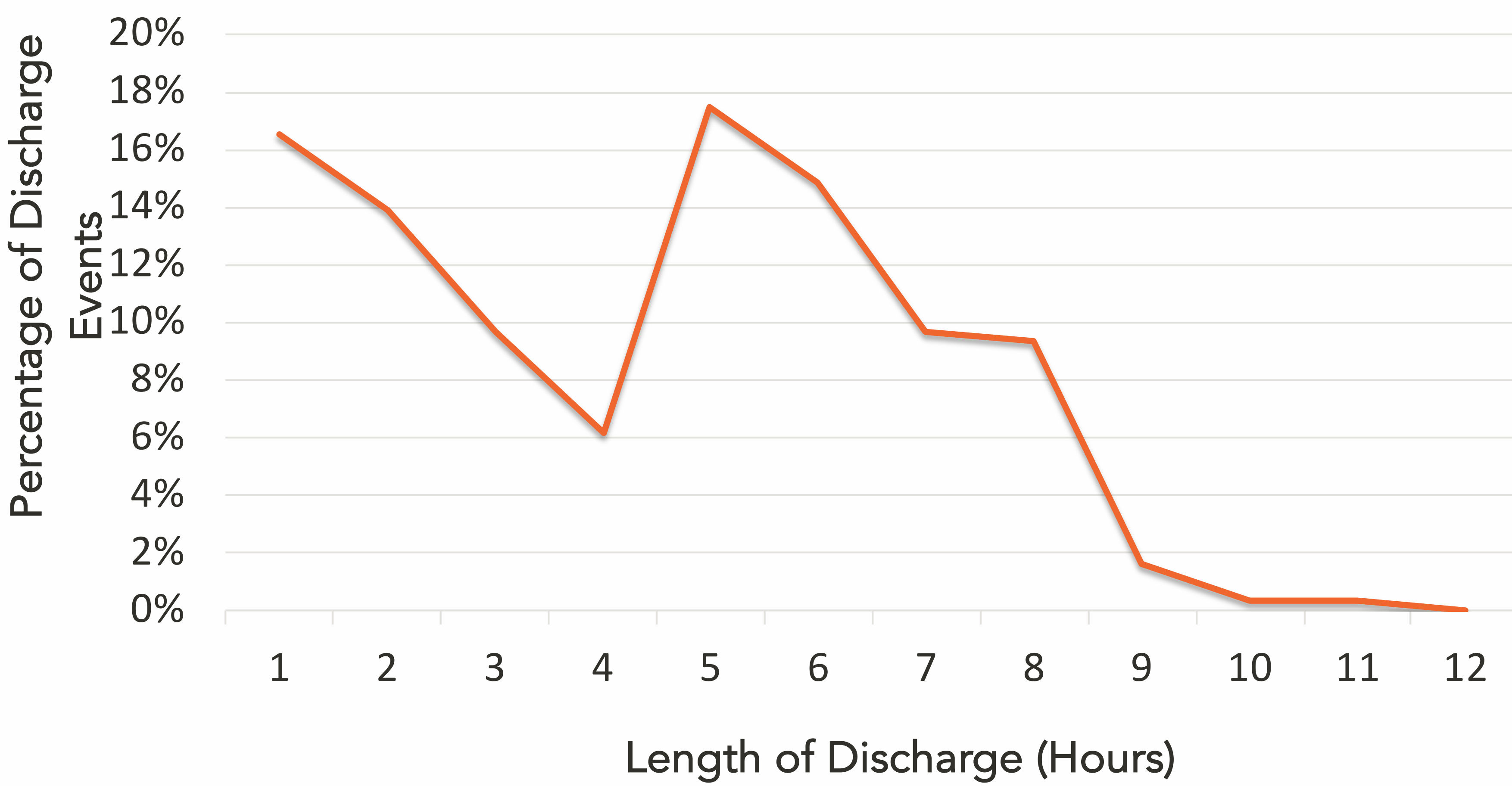
Frequency of Different Discharge Durations



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Report Advisors

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Bruce Phillips	Director, The NorthBridge Group
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