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Research Brief

Steady Heat, Flexible Power: Flexibility by Proxy in Nuclear-Thermal Energy Storage Systems

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We use a capacity expansion and dispatch model to study the value of integrating a Thermal Energy Storage (TES) system into a fusion power plant. Storage enables the plant to run the fusion reactor at very high capacity factors, while generation of electricity fluctuates significantly. This enables penetration of fusion even at relatively high capital costs.

Thermal Energy Storage (TES) is a promising technology to reconcile the economic constraints of capital-intensive low-carbon thermal generators such as nuclear power plants with the operational flexibility required in deeply decarbonized systems. The increasing penetration of variable renewable energy drives a growing spread in the marginal value of generation across hours through a day and throughout the year. On the one hand, when renewables are plentiful and net load is small or even zero, the marginal value of generation is zero. On the other hand, when there is a drought of renewable energy and net load threatens to exceed firm capacity, the marginal value of generation spikes. Integrating Thermal Energy Storage enables baseload production of heat, even during hours when the marginal value of electricity is low, which can then be converted to electricity when the marginal value of generation is high. This creates a new operational paradigm in which nuclear assets can behave simultaneously as firm baseload providers to maximize rate-of-return and as flexible resources to match system needs.

We employ the GenX Capacity Expansion and Dispatch Model to assess the system value of integrating Thermal Energy Storage into a fusion power plant. We parameterize our GenX model to match a 2050, deeply decarbonized New England grid, and we use GenX to co optimize investment and hourly operation across a portfolio of competing low carbon technologies. Our results show that Thermal Energy Storage fundamentally reshapes the economic frontier for fusion, dramatically increasing the breakeven cost at which investment is cost-effective for the grid, from 8,000 $\$/\text{kW}_e$ up to 19,000 $\$/\text{kW}_e$. Incorporating TES and therefore deploying fusion compresses the spread in the marginal value of generation across hours of the day and through seasons of the year. Our model optimizes the size of the TES energy reservoir as well as the size of the turbine generating electricity. The optimized TES includes a very large energy reservoir, giving the TES the ability to deliver power for a long duration of 10 hours. We analyze the operation of the TES and contrast it with the operation of other storage technologies.

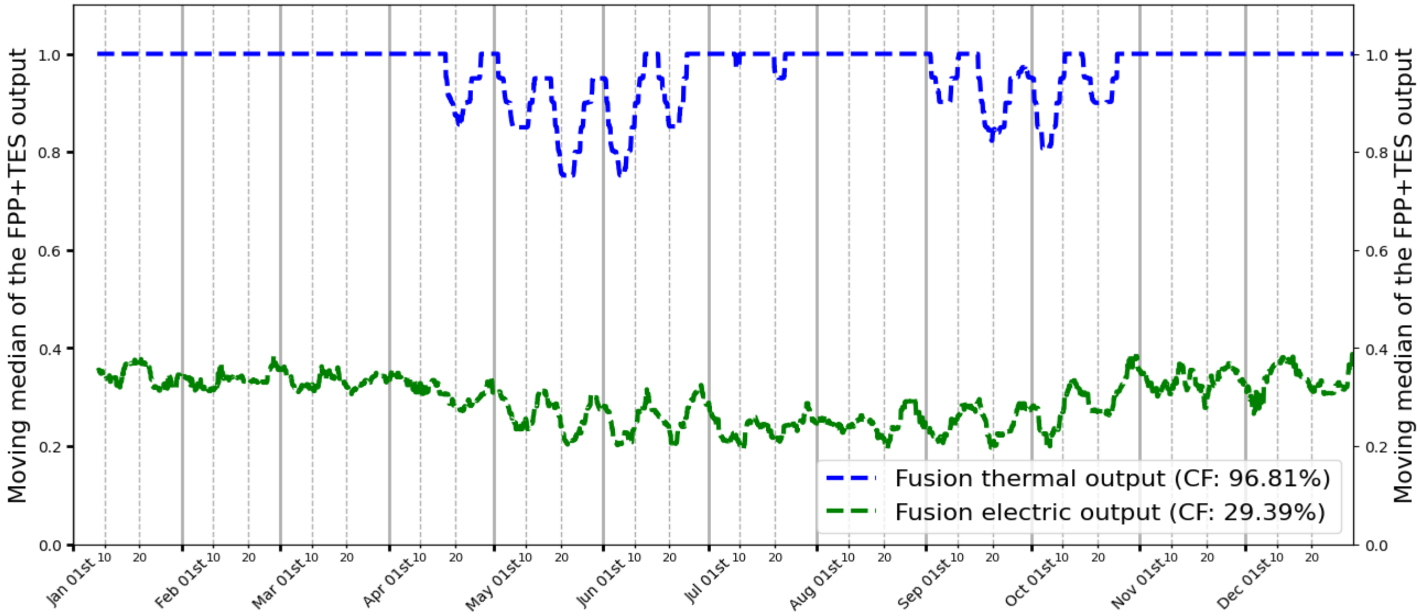

Figure 1: Median weekly heat and electricity production through an average year.

We use the GenX model described in Armstrong et al. 2024. Generating technologies available in the model include utility-scale PV, commercial rooftop PV, residential PV, onshore wind, fixed offshore wind, floating offshore wind, legacy run-of-river hydro, natural gas combined-cycle, and natural gas combined-cycle outfitted with carbon capture and sequestration. Storage technologies include legacy pumped hydro-facilities as well as Li-ion batteries. Notably, since New England imports a significant amount of power from Quebec's large hydro system, the model also includes an hourly load profile in Quebec, together with an hourly water inflow profile, and the model optimizes the exports of power to New England while respecting specified reservoir system constraints such as minflow and seasonal maximum capacities. A distinctive feature of that model is its parameterization with 20 scenario years for hourly load and wind and solar resource availability, so that the chosen portfolio of investments must be robust across the range of scenario years. In this paper, the carbon limit is 12 gCO$_2$/kWh$_e$, a 95 % reduction relative to 1990.

Alongside the other generation technologies, Armstrong et al. 2024 introduce a tokamak-type fusion power plant. The representation of a thermal power plant in GenX involves only a few essential parameters, such as thermal efficiency and operational constraints, and does not require elaboration of the many details particular to this or that fusion plant. Nevertheless, to fix ideas, we briefly describe a few selected features of a generic, imagined deuterium-tritium magnetic confinement fusion power plant. The base case plant's total thermal power capacity to 1,095 MW$_{th}$. Turbine efficiency is 40 %, in which case the plant's gross electric power capacity is 438 MW$_e$. Some 111 MW$_e$ of power is needed for station load within the plant to cool the magnets, drive the fusion reactor, pump the molten blanket, and supply electric power for the tritium processing system and other plant operations. Thus, the net electric capacity is 327 MW$_e$. For our modeling, it will be important to understand how the station load varies as the thermal power is ramped down. Besides a permanent station load of 10 MW$_e$, we assume FixedSL = 10 MW$_e$ is the fixed load and VarSL = 0.083 MW$_e$/MW$_{th}$ is the variable load. The Fusion Power Plant can balance its self-consumption by collecting part of its electricity generation or by consuming electricity from the grid. Overall, the plant's heat-to-electricity efficiency is η_{FPP} = 29.4 %.

We model the TES in a direct architecture in which the fusion plant provides thermal energy to the salt loop which independently supplies the turbine loop. The TES charges when the plant provides more energy to the salt loop than the salt loop discharges to the turbine, and excess salt is transferred from the cold tank (light blue) to the hot tank (light red). Conversely, the TES discharges when the salt loop discharges more energy to the turbine than it receives from the plant, transferring salt from the hot tank to the cold tank and boosting generation at the turbine.

Table 1 shows the optimized portfolio and dispatch, first assuming the fusion plant is only available without TES, and second assuming TES is integrated into the fusion power plant. The assumed cost of the base fusion plant is $\$8{,}500/\text{kW}_e$. At that cost, and without TES, the optimized portfolio does not include any investment in fusion capacity. However, when TES is integrated into the fusion plant, the optimized portfolio does include investment in fusion capacity—7.7 GW_e of turbine capacity generating 17.46 TWh of electricity.

Our model optimally sizes both the power and the energy capacity of the TES, and we find that it chooses very long durations. The TES has a lower turnover than grid batteries, but a higher utilization. The TES captures a higher spread on its turnovers than grid batteries, and its operating profitability is more concentrated in a fewer number of hours.

	Without TES			With TES		
	Capacity (GW_e)	Generation (TWh_e)	Capacity Factor	Capacity (GW_e)	Generation (TWh_e)	Capacity Factor
Natural gas	8.9	2.21	3%	9.8	2.83	3%
Natural gas w/ CCS	23.1	50.83	25%	19.4	46.11	27%
Solar PV	22.0	27.59	14%	22.0	27.7	14%
Onshore wind	9.0	30.27	38%	9.0	30.47	39%
Offshore wind (fixed)	27.3	114.79	48%	23.3	98.37	48%
Run-of-river hydro	2.0	7.78	45%	2.0	7.78	44%
Fusion	0.0	0.00		7.7	17.46	26%
Pumped hydro	1.8	2.61		1.8	1.97	
Battery	18.6	25.48		12.5	13.55	
Total	112.7	261.56		107.5	246.24	
Net imports	2.3	13.15		2.3	13.59	
Total generation		233.48			230.72	
Storage charge		-33.32			-18.44	
Storage discharge		28.09			15.52	
Net Energy supplied		241.39			241.39	

Table 1: Optimized Capacity Portfolios and Dispatch, Without and With TES Integrated with the Fusion Power Plant.

References

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Link to the full working paper discussed in this brief:

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About the Authors

Nicolas Trosino is a Fulbright Ph.D. Candidate conducting research at the Laboratoire de Génie Industriel (LGI - SERG) of CentraleSupélec (Paris-Saclay University) and at the Massachusetts Institute of Technology (MIT Energy Initiative). He has graduated from the École normale supérieure Paris-Saclay in 2023, in both applied physics and economics, and from CentraleSupélec in 2023 in energy physics and engineering. In 2024, he studied the integration of flexibility constraints of light-water pressurized reactors in Capacity Expansion and Dispatch Models for the French Atomic Commission. His current PhD research draws on HEXANA commitment to decarbonize beyond electricity, by coupling next-generation nuclear assets, thermal energy storage, and non-electric end use.

Dr. John Parsons is the Deputy Director for Research at the MIT Center for Energy and Environmental Policy Research (CEEPR). His research focuses on the valuation and financing of investments in energy markets. Recent publications have touched on interregional transmission investments, including the interaction with hydro assets and expanded penetration of renewables, the value of investments in life extensions of nuclear power plants, and the economics of new microreactors. He has served as an Associate Member of the U.S. Commodity Futures Trading Commission's Energy and Environmental Markets Advisory Committee and has been a Visiting Scholar at the Federal Energy Regulatory Commission. John received his B.A. in economics from Princeton University, and an M.A. and Ph.D. in economics from Northwestern University.

Dr. Ruaridh Macdonald is the Energy Systems Research Lead at the MIT Energy Initiative. His research explores how best to decarbonize the electricity grid and other sectors, and which technologies and policies will reduce the cost of the energy transition while also ensuring grid resilience and security. He is developing novel approaches to macro-energy system modelling which allow for larger multi-sector energy systems to be optimized over long time periods. This allows for technologies to be modelled with greater fidelity and considering interannual variation in energy supply and demand. Ruaridh is a co-lead developer of the GenX and DOLPHYN macro-energy system models. He completed his PhD in Nuclear Science and Engineering at MIT.

Dr. Charles Forsberg is a nuclear chemical engineer. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory. He led the MIT Future of the Nuclear Fuel Cycle study and is the PI building a flowing salt loop at the MIT reactor to better understand flowing salts under irradiation fields in support of salt-cooled reactors. He is one of the three co-inventors of the Fluoride-salt-cooled High-temperature Reactor (FHR). A 35-MWt FHR test reactor is under construction in Oak Ridge, Tennessee by Kairos Power. Dr Forsberg is a co-inventor of electrically conductive firebrick to enable conversion of low-price electricity into stored heat up to 1800°C. It is the enabling technology for nuclear thermodynamic power topping cycles to provide dispatchable peak electricity from base-load nuclear power plants. He teaches classes in nuclear chemical engineering and waste management and has published over 300 papers and 13 patents.

Dr. Yannick Perez is a Full Professor of Economics at CentraleSupélec (University Paris-Saclay). He received his PhD in economics from La Sorbonne in 2002 and has been the chief economic advisor of the Loyola de Palacio Chair on European Energy Policy at the European University Institute in Florence from 2008 to 2023. In 2012, he joined the Armand Peugeot research chair on Electromobility as a Senior Research Fellow. He became in 2024 the director of the Open Lab Carbon Economics for Mobility (OLCEM), a research initiative between CentraleSupélec and Stellantis and in 2025 the co-director of the Center of Energy Markets and Sustainable Industries (CEMSI) sponsored by EDF, Deloitte, RTE, and Stellantis. He supervised 20+ PhD thesis, and his research focusses on electricity market design, using methods from industrial organization and microeconomics.

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