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RESEARCH DIGEST

The value of fusion energy to a decarbonized United States electric grid

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Fusion technology has been receiving increased attention from governments and private companies, with over $3.4B invested in the last year alone. Fusion plants could provide a carbon-free firm source of electricity in a compact footprint. There are a variety of fusion plant concepts being pursued, which will have different cost and performance characteristics. While we model pulsed tokamaks, our work is relevant to most fusion concepts. We study the value that fusion could provide to a future decarbonized electricity system in the eastern United States, and generate cost targets for fusion to be economically competitive in a set of future scenarios. To reach 100 GW of capacity, fusion plants require capital costs of under $3/W to under $7.5/W, depending on the plant's variable operational costs and the costs of its competitor resources. While pulsed tokamaks must periodically pause their heat generation, and may require a large but brief power draw from the grid in order to restart, this was found not to strongly impact the value of the plant. Integrating thermal storage into a fusion plant, which would allow it to shift power generation to the times of day when it is most needed, could add up to $0.7/W to the value of the fusion core. Fusion competes with other low-variable-cost firm resources such as fission; in scenarios without fission or where fission has been displaced, it competes with a combination of renewables and storage.

Fusion plants could be a valuable source of firm, carbon-free electricity in future decades. In fusion reactors, atomic nuclei are combined using reactions that occur at extremely high temperatures in an ionized gas, called *plasma*. The reaction products are energetic particles, which are typically used to heat a working fluid (such as steam) which then turns a turbine, generating electricity. The means of electricity generation is like that in coal or fission plants, though the reaction chamber itself is very different due to the physical principles involved. The fuel for the reaction is abundant and low-cost, but many designs will require replacements of components worn out by exposure to the energetic reaction products and the plasma itself; this would result in *variable operations and maintenance* costs which must be considered. And, while some concepts promise continuous power generation, pulsed tokamaks, the most well-developed concept, require stopping the reaction after some time, typically a fraction of an hour to a few hours, in order to reset certain systems. Starting the reactor requires a burst of electrical power of a few seconds to minutes, either from some form of energy storage on-site or drawn from the external electric grid. Pulsed tokamaks may also incorporate thermal energy storage systems, which could allow shifting their electrical generation to hours when power is most needed on the grid. Since many of the design parameters are still to be determined, and the technology is in early stages of development, it is difficult to precisely estimate the capital and variable costs of a fusion plant.

Princeton University's Zero-carbon Energy systems Research and Optimization Laboratory conducts research to improve decision-making and accelerate rapid, affordable, and effective transitions to net-zero carbon energy systems. Prof. Jesse D. Jenkins is the Principal Investigator. For more, see zerolab.princeton.edu.

Princeton University's Plasma Control Lab conducts research on machine learning for fusion applications, real-time plasma control, stellarator optimization, liquid metal technology, and more. Prof. Egemen Kolemen is the Principal Investigator. For more, see control.princeton.edu.

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In our new peer-reviewed paper, in press in the journal *Joule*, we study pulsed tokamaks with a wide range of variable operational costs and pulse cycle parameters. We determine the *value* that these plants would provide to decarbonized electricity systems in the eastern United States in the year 2050. The value of the plant is set by the costs of the resources (including other generators and their fuels, energy storage, and transmission lines) that fusion would substitute for in an electricity system optimized for the lowest total annual cost. It is equivalently the "cost threshold" that fusion much reach for its deployment to be economical. We explore three "market opportunity" scenarios which vary the costs of fusion's competition. In each scenario, we determine the maximum capital cost to reach a range of installed capacities. Additionally, we identify the parameters that most strongly affect the value of a fusion plant. In a second study, we determine the value added by integrating a thermal storage system, such as a molten salt tank, to increase the operational flexibility of the plant.

Methods

Our study, summarized in this research digest, uses optimization modeling to represent the operation of fusion reactors in future electricity systems. Fusion plants have three components: a fusion core, which takes in parasitic "recirculating" power from the electric grid and generates heat, an optional thermal storage system (TSS) which can store the heat generated, and a power conversion system which converts heat from the core or TSS to electric power on the grid. The core and generator have associated variable operational costs; additionally, the core always draws parasitic power from the grid, and additional parasitic power while operating. The core must turn off after a specified number of hours of operation; to restart, there must be sufficient excess power capacity in the geographic zone in which the reactor is located to handle the brief start-up load.

The fusion framework described above is incorporated as a new technology module into GenX, an open-source electricity systems optimization model that determines an optimal set of investment and operational decisions to minimize the cost of meeting electricity demand over the course of a planning year, subject to policy and operational constraints. We use GenX to model least-cost decarbonized electricity systems in the eastern United States in the year 2050, exploring a range of scenarios that vary the cost and performance of fusion and competing technologies. We define three reference tokamaks: an "optimistic" design with low variable costs ($4.5/MWh) and no pulse constraints, a "pessimistic" design with high variable costs ($26/MWh) and severe pulse constraints, and a "mid-range" design between the two ($11/MWh). The study of plants with integrated thermal storage examines a range of storage capacity costs, from $11/kWh to $44/kWh.

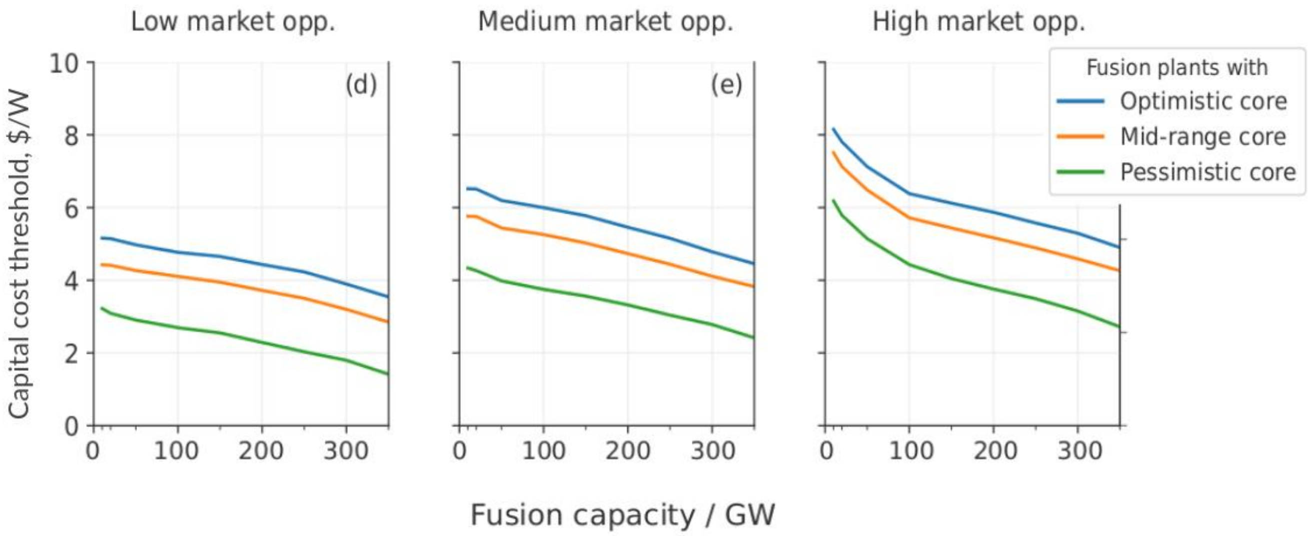


Figure 1: Cost thresholds for the three fusion plant designs to reach a given capacity in the low, medium, and high "Fusion market opportunity" scenarios. For reference, the average system load is 600 GW, and the peak load is 1100 GW.

Findings

Fusion could play a significant role in a future decarbonized electric grid, if it can meet cost targets. An initial penetration into the market (10 GW of total capacity) would require capital costs of $3/W to $8/W, depending on the market scenario and the reactor design. To reach 100 GW in a long-run equilibrium would require capital costs of under $6.5/W. For comparison, the ARIES-AT tokamak study found a capital cost of about $5/W, but this on the low end of published tokamak cost studies. If fusion costs are over $10/W, it would not be part of a least-cost electrical system, even in scenarios where new-build fission and natural gas with carbon capture and storage (NG-CCS) are forbidden.

Fusion's first competitor is fission. The two technologies are both capital-intensive and have broadly similar variable operational costs, so they play similar roles in the electricity market. Provided that new-build fission is available, fusion will need to compete directly with it, such that if the cost of fusion is low enough it could replace the need for new fission. At even lower costs, fusion would compete with a combination of solar, energy storage, and natural gas with carbon capture and storage (NG-CCS). In this regime, fusion energy substitutes primarily for solar energy if fusion's variable costs are low, and primarily for energy produced by NG-CCS if its variable costs are relatively high.

The value of a fusion plant depends strongly on its variable operational cost, and only weakly on hourly-scale operational constraints. When computing the "capital cost per watt" metric for a pulsed tokamak fusion plant, the denominator should be the time-averaged net electric power produced, not the peak power output. Cast in these units, the difference in value between the "optimistic" and "pessimistic" reference plants is due almost entirely to the difference in their variable operational costs, not the differences in their pulse cycle parameters: the pessimistic plant has a value about 6% lower than a plant with no pulse constraints but the same variable cost. The decision to choose a pulsed or steady-state tokamak should be made by weighing the technical issues and costs involved; in our model they present a similar value to the energy market.

Integrated thermal storage could enhance the value of fusion, by a modest amount. Integrated thermal storage could allow a fusion plant to shift its electrical output to hours when solar power is not available. The option to build thermal storage becomes more valuable as the plant's variable operational cost and the capacity cost of the storage decrease. The value of the fusion core for a plant with a $4/MWh variable operational cost and a $22/kWh storage capacity cost, similar to that of molten salt tanks, increases by $0.2/W and $0.7/W in the "low" and "high" fusion market opportunity scenarios, respectively. The plant would include storage for 4 to 8 core-hours of heat, and the power conversion system is sized to handle 120% to 140% of the core's peak output power (drawing heat from both the core and the storage system), which lets it concentrate generation during the valuable evening hours.

The equilibrium fusion capacity increases strongly as cost decreases. If fusion can make an initial penetration into the market, then further cost decreases (via experience-based learning) could lead to significant adoption of fusion. For example, in the "medium market opportunity" scenario, a cost decrease of $0.5/W could increase the equilibrium fusion capacity from 10 GW to 100 GW.

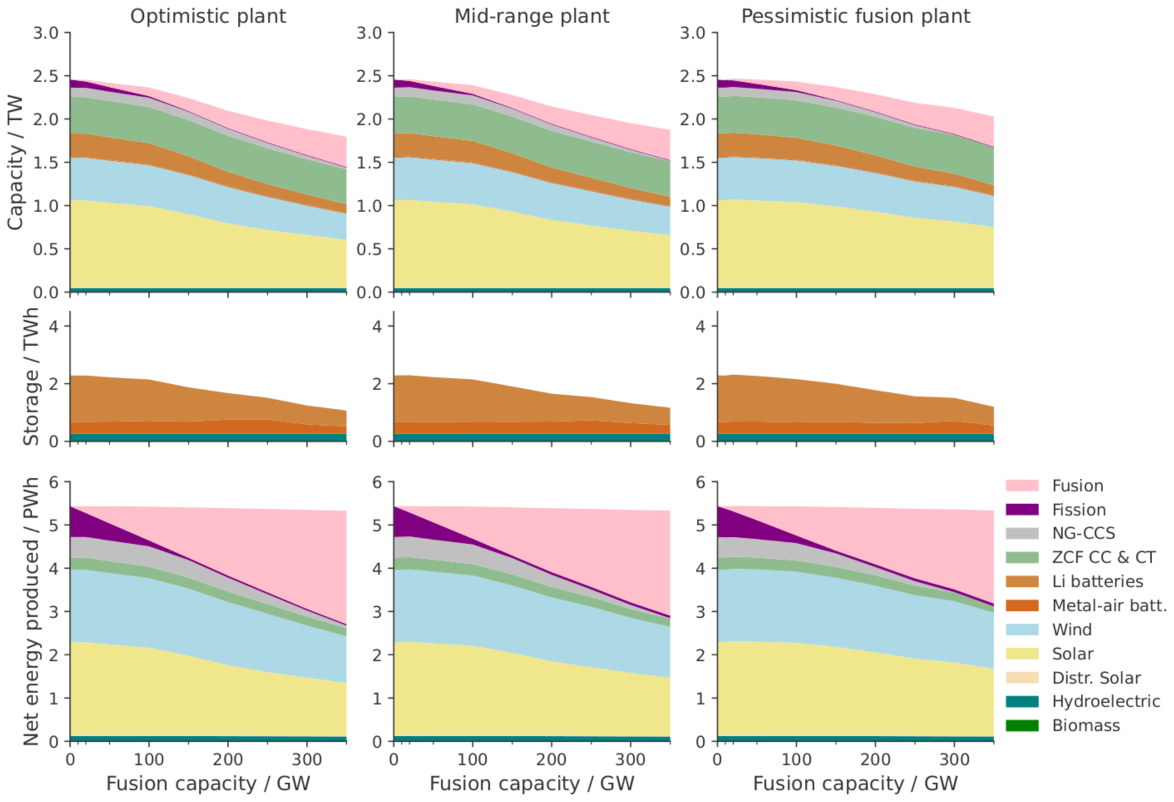
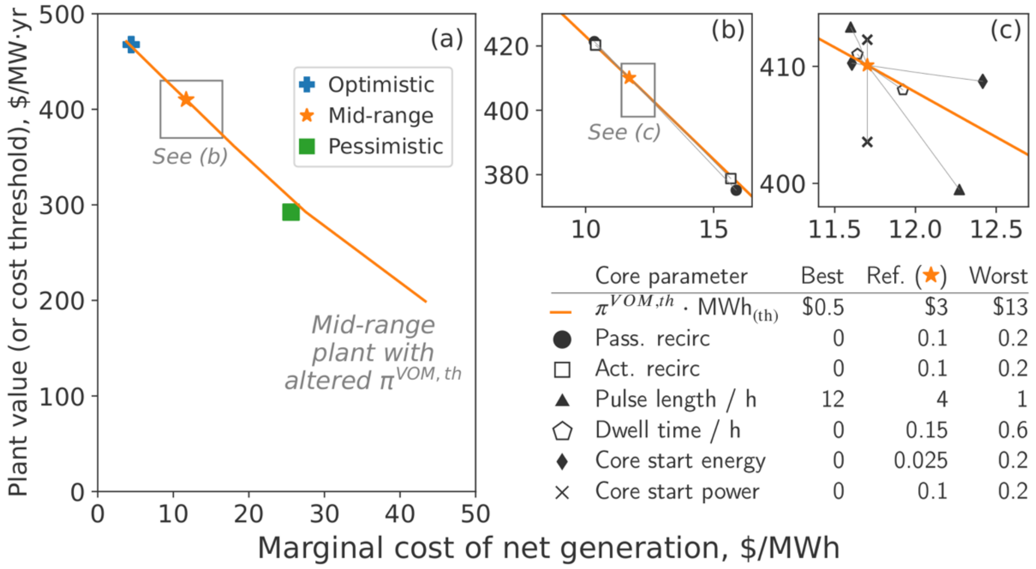


Figure 2: Optimal system configurations as functions of installed fusion capacity, in the medium fusion market opportunity scenario, for the three reference fusion reactor designs. New-build fission is an immediate competitor to fusion in this scenario. If the fusion cost is low enough that no fission is constructed, fusion competes with a combination of solar, wind, Li batteries, and natural gas plants with CCS (Carbon Capture and Storage), but not with combined cycle plants and combustion turbines burning zero-carbon fuels (ZCF).



	Core parameter	Best	Ref. (★)	Worst
—	$\pi^{VOM,th}\cdot$ MWh$_{(th)}$	\$0.5	\$3	\$13
●	Pass. recirc	0	0.1	0.2
□	Act. recirc	0	0.1	0.2
▲	Pulse length / h	12	4	1
⬠	Dwell time / h	0	0.15	0.6
♦	Core start energy	0	0.025	0.2
×	Core start power	0	0.1	0.2

Figure 3: The value of a pulsed tokamak plant is strongly determined by its variable operations and maintenance cost (the marginal cost of net generation), much more so than by the pulse behavior. Part (a) shows the value of the three reference plants as a function of their variable cost, and the value of plants with a pulse behavior like that of the mid-range reactor but with an altered variable cost. The value of the pessimistic plant is only about 4% lower than that of the mid-range-like plant with the same variable cost. Parts (b) and (c), insets of (a), show that varying the operational parameters of a mid-range plant results in only small deviations in its value. The table shows the ranges over which the parameters were varied.

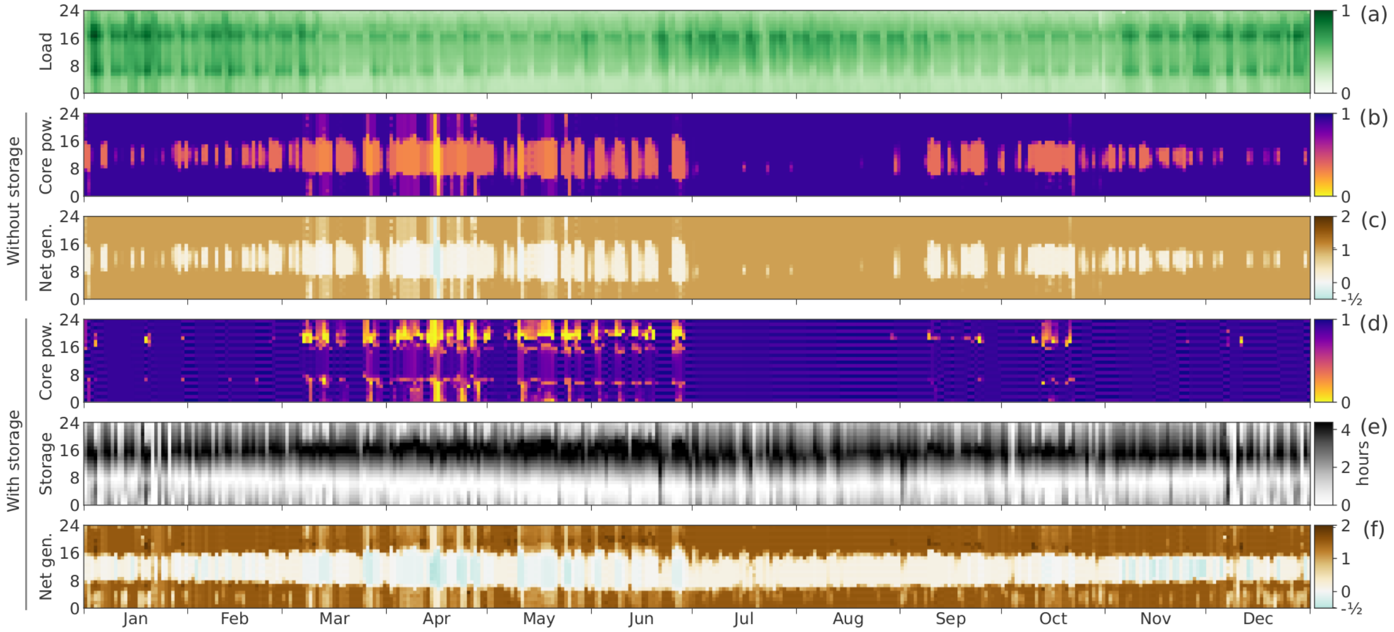


Figure 4: Hourly operational patterns throughout the year for fusion plants of the pessimistic design in the PJM-Mid-Atlantic region. Part (a) shows the normalized hourly load in the region. Parts (b) and (c) show the operation of the core and the net output of a plant without integrated thermal storage; during a brief period the plant is a net sink of energy due to its parasitic power requirements. Parts (d) through (f) depict the operation of a plant with about 4 core-hours of storage, with part (e) showing the level of energy in the thermal storage system. With storage, the plant concentrates its generation during the night-time hours when its power is most valuable, even using solar power during the day to run the core and generate heat while the power conversion system idles.

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