MIT CEEPR
Center for Energy and Environmental Policy Research

Working Paper Series

Is Fusion Too Late? How Investors Value its Role in a Decarbonized Europe

Sophia A. E. Spitzer, Katja Pelzer, Anton Bauer, and Maximilian J. Blaschke

OCTOBER 2025

CEEPR WP 2025-20

Working Paper Series.

Since 1977, the Center for Energy and Environmental Policy Research (CEEPR) has been a focal point for research on energy and environmental policy at MIT. CEEPR promotes rigorous, objective research for improved decision making in government and the private sector, and secures the relevance of its work through close cooperation with industry partners from around the globe. Drawing on the unparalleled resources available at MIT, affiliated faculty and research staff as well as international research associates contribute to the empirical study of a wide range of policy issues related to energy supply, energy demand, and the environment.

An important dissemination channel for these research efforts is the MIT CEEPR Working Paper series. CEEPR releases Working Papers written by researchers from MIT and other academic institutions in order to enable timely consideration and reaction to energy and environmental policy research, but does not conduct a selection process or peer review prior to posting. CEEPR's posting of a Working Paper, therefore, does not constitute an endorsement of the accuracy or merit of the Working Paper. If you have questions about a particular Working Paper, please contact the authors or their home institutions.

Is fusion too late? How investors value its role in a decarbonized Europe

Sophia A. E. Spitzer[1,2,*], Katja Pelzer[1], Anton Bauer[1], Maximilian J. Blaschke[1,3]

[1] TUM School of Management, Technical University of Munich, Munich, Germany

[2] Marvel Fusion GmbH, Munich, Germany

[3] Center for Energy and Environmental Policy Research, Massachusetts Institute of Technology, Cambridge, MA, USA

[*] Correspondence: sophia.spitzer@tum.de

October 9, 2025

Abstract

Fusion energy promises clean, firm, and geographically flexible power, making it a potentially breakthrough technology for global decarbonization. However, uncertainty regarding its commercialization timeline and the rapid expansion of renewable energy question its role in future energy systems. Using a high-resolution energy system model (PyPSA-Eur) and a probabilistic valuation framework, we find market expectations on fusion's successful commercialization to be low in light of recent fusion investments. With estimated probabilities below 20% in most cases, fusion's commercialization prospects are seen as limited, despite its high long-term system value, reducing energy system costs and reliance on complementary renewable integration technologies. Our results indicate that the later fusion becomes available, the greater will be the demands on its economic competitiveness and the need for early integration into energy system planning. The misalignment between system benefits and current investments may reflect a rational response to deep uncertainty, yet it may perpetuate a high-risk, high-reward paradox typical of breakthrough technologies. Recognizing this ambiguity calls for a more deliberate evaluation of fusion's role in future energy systems.

***Keywords*—** Fusion energy, fusion power plants, energy system optimization, binomial decision, PyPSA-Eur, anticipated commercialization probability

1. Introduction

Fusion energy is widely regarded as having the potential to meet the world's growing hunger for energy, offering several advantages for effective system decarbonization. It is considered clean, firm, geographically flexible, highly energy-dense, and virtually inexhaustible[1–4]. However, fusion energy has struggled to meet expectations for decades, as promised milestones have been repeatedly missed — fueling the notion of a 'fusion constant', the idea that fusion is perpetually 30 years away[5,6]. Nevertheless, two recent trends may signal a turning point in fusion energy development. First, expert estimates of the time to commercialization have declined - from over fifty years in the early 2000's to approximately 20 years in the 2020's[2] - following a series of scientific breakthroughs[7,8]. Second, an increasing number of private ventures have committed to delivering competitive fusion energy by the 2030's[6,9]. Just over recent years, several fusion start-ups have raised considerable funding[9].

Still, until further technological breakthroughs bring clarity, fusion's successful commercialization and its timing remain uncertain. Amid this uncertainty and the threatening climate crisis, countries around the world have to heavily invest in wind and solar energy to achieve carbon neutrality, despite the high system costs associated with fully renewable energy systems[10]. This raises fundamental questions:

What impact could fusion still have if it arrives in 10 or 20 years? Could fusion be too late if decarbonization is already achieved by other means? What do today's investments in fusion reveal about its chances of successful commercialization?

A common way to analyze the contribution of fusion energy to the generation mix of the future is energy system optimization[11]. A structured literature review of the past two decades reveals projected market shares for fusion energy in global electricity generation ranging from as low as 0.1%[12] to as high as 80% by the end of the century[13] (see Table 1 and Figure A.4 in the supplementary information for a summary). These projections are highly sensitive to three key factors: the timeline for fusion's commercial introduction, capital cost assumptions, and capacity constraints.

The timeline for fusion deployment significantly impacts its market share. A 10-year delay (from 2050 to 2060) in an unconstrained build-out scenario can reduce fusion's contribution by roughly 10%, while a 20-year delay results in a reduction exceeding 50%[13]. Similarly, a 15-year delay (from 2035 to 2050) could decrease the market share by approximately one-third and market value (defined as cost savings potential) by a factor of 2–14[14]. Together, these findings emphasize the time sensitivity of fusion energy's market adoption and its broader economic implications.

Capital cost assumptions emerge as another particularly influential driver of these projections, as emphasized throughout the academic discourse[12–18]. Given the considerable uncertainty surrounding fusion cost estimates, the wide range of projected market shares reflects the technology's highly conditional addressable market potential — realizable only if specific cost thresholds are met.

Capacity constraints, often introduced to account for structural diffusion inertia, further refine these estimates but have received limited critical attention in the literature. Existing studies frequently impose exogenous limits, such as capping fusion deployment at 50 GW in Europe by 2100[15], 100 GW in the U.S.by 2050[3], or an annual build-out limit of 2 GW per region[12] and 100

GW globally[13]. More recent analyses incorporate dynamic ramp-up trajectories based on historical diffusion patterns of power generation technologies[19,20]. The authors argue that fusion adoption is ultimately constrained by industrial scalability — specifically the doubling time — once investment costs fall below critical thresholds[19]. This reliance on externally defined constraints is especially visible when contrasting projections: unconstrained scenarios estimate that fusion could supply up to 80% of electricity by 2100, positioning it as a dominant source in the latter half of the century, whereas capacity restrictions reduce this share to around 20%[13]. While such constraints are useful to capture plausible deployment barriers, they may also obscure the underlying dynamics of fusion deployment. Exploring unconstrained scenarios, though inherently idealized, can yield valuable insights into fusion's theoretical contribution and help evaluate the scale of effort needed to bridge the gap between potential and realistic deployment.

Regional variation and technological uncertainty contribute substantially to the wide range of estimates for fusion's role in future electricity systems. Large-scale adoption in the United States and Western Europe remains contested: some studies project substantial market shares[15,16,22], while others expect significant uptake only in regions with particularly high demand growth (Asia post-2050[19] or in countries such as Japan, South Korea, or Turkey, where low-emission alternatives are more limited[12]. Diverging projections partly reflect methodological differences; some analyses neglect broader grid integration[16] or impose strict exogenous capacity caps[15], highlighting the need for more granular, interconnected models to assess regional deployment pathways. This issue warrants closer examination, given that the United States and Europe are among the primary sources of fusion financing. Cost impacts also vary widely: unconstrained scenarios indicate annual system cost reductions of up to 8.5%[13], while even constrained cases report benefits such as a 4% decrease in Europe's system-levelized cost of electricity[15]. Fusion's contribution is particularly valuable in systems with high shares of renewables, where it reduces installed capacity, storage requirements, and curtailment, thereby lowering overall system costs[16]. Global estimates suggest long-term cost savings could range from hundreds of billions to tens of trillions of dollars, with a median of USD_{2012} 2.2 trillion, implying that current R&D and public investment levels may not fully reflect this potential[14].

Hence, existing studies demonstrate that fusion energy could play a significant role in the energy system of the future. However, any assessments of its potential role remain inherently speculative given the substantial uncertainty surrounding both the success and timing of fusion deployment. This highlights the need for a more robust evaluation framework — one that explicitly accounts for uncertainty and the relationship between investment levels and commercialization prospects, supported by detailed modeling of grid interconnections, regional renewable resources, and alternative low-carbon technologies. Building on prior work[13–16], this study introduces a holistic energy system optimization framework that integrates fusion energy into a pan-European context. Our approach incorporates the existing renewable electricity infrastructure, reflects the spatial and temporal heterogeneity of the European grid, and considers different commercialization timelines for fusion. Specifically, we implement fusion power plants into PyPSA-Eur and simulate system development between 2030 and 2100, applying high-resolution spatial and temporal modeling. This level of granularity represents a methodological advancement in the literature, particularly with a European focus. We quantify fusion's value through system-wide cost savings and interpret the re-

Table 1: ***Summary of literature estimates for fusion energy deployment.*** *Key parameters from existing studies on fusion's projected role in future electricity systems, including regional scope, assumed introduction year, overnight capital cost (OCC) range, capacity constraints, and estimated generation share. See footnotes for details on assumptions and conversions.*

Source	Regional Focus	Comm.Year (first installation)	OCC [USD_{2020}/kW]	Capacity Constraint	Generation Share (Max.) [%]
[13]	Global	2050	2,375 - 4,434	100 GW p.a.	20 (80)
[21]	Global	2060	N/A[1]	330 - 950 GW	20 (52)
[22]	Global	2050 (2080)	5,706 - 8,559	N/A	15[2] (20)
[18]	Global	2050	3,879 +/- 20%[3]	26% growth p.a.	30 (76)
[14]	Global	2035	6,222 +/- 30%[3]	N/A	39 (53)
[17]	Global	2050 (2070)	5,777 +/- 30%[3]	N/A	13 (42)
[16]	UK, Italy	2080	6,696 +/- 30%[4]	Exogenous capacity assumption	43
[15]	Europe	2060	3,348 - 11,160 [4]	50 GW	4 - 9
[12]	Global	2050	6,497 - 8,368	2 GW p.a. per region	0.5[5]
[3]	U.S.	2035	3,561 - 5,697	100 GW	N/A [6]
[19]	Global	2035 (2050)	5,035 (2035) - 2,660 (2050)	Based on[20]	10 (15)

[1] *Only LCOE at 50 - 90 USD/MWh given.*

[2] *Estimate based on 30% share of nuclear with 60%.*

[3] *Progressive cost degression assumed:[18] progress ratio of 0.81;[14] progress ratio of 0.9;[17] cost decrease from 5,777 USD/kW (2050) to 3,182 USD/kW (2080).*

[4] *EUR values converted to USD at a 1:1.1 conversion rate.*

[5] *High regional dependence of results, i.e., 0.1% in Europe, 25% in Japan.*

[6] *Only capacity share given at 32% for 3,561* USD_{2020}/kW_{el}

sulting discounted savings as the potential returns investors may expect from the technology. Based on this, we apply a probability-based real options framework to infer implicit investor beliefs about fusion's likelihood of commercialization at various points in time. Further, we introduce a novel concept: The Anticipated Commercialization Probability (ACP), which connects system-level cost savings from fusion with investment expectations through a probability-based real options framework. This metric provides a probabilistic lens to assess how investors implicitly value fusion's success, offering a fresh perspective on strategic decision-making under deep uncertainty.

Our results underscore fusion's significant potential under low to medium cost assumptions and emphasize the critical role of capacity constraints in shaping model outcomes. The findings suggest that beyond the debate on fusion's availability timeline, equal attention must be paid to accelerating industrial scale-up, e.g., by easing regulatory bottlenecks or by promoting technological learning to enable timely deployment.

2. Results

We assess the value of fusion energy in a future European energy system with a two-fold research design combining energy system optimization with probabilistic valuation. We first quantify fusion's potential system-wide cost savings and then compare these benefits to observed investments in a simple binomial decision. This integrated approach allows us to calculate the ACP, which captures the investor expectations of fusion success under uncertainty and helps justify current private and public funding levels in light of fusion's long-term value.

We begin by calculating the cumulative costs of the energy system from $t_0 = 2030$ to $T = 2100$, discounted to the base year t_0, applying the social discount rate r_s. This is done for both the baseline scenario without fusion, denoted as $C_{sys,nofus}$, and the scenario with fusion, denoted as $C_{sys,fus,\alpha}$, for a range of scenarios α from the scenario set S. These scenarios account for variations in key factors such as fusion plant capital cost, deployment start year, and capacity limits, as defined in subsection 4.2. We then quantify the value of fusion energy, $V_{fus,\alpha}$, as the difference between the cumulative system costs in the reference scenario (no fusion) and the scenario with fusion[14].

$$\begin{aligned} V_{fus,\alpha} &= \sum_{t=t_0}^{T} C_{sys,nofus,t} * (1+r_s)^{-(T-t0)} - \sum_{t=t_0}^{T} C_{sys,fus,\alpha,t} * (1+r_s)^{-(T-t0)} \\ &= \sum_{t=t_0}^{T} \Delta C_{sys,\alpha,t} * (1+r_s)^{-(T-t0)} \end{aligned} \tag{1}$$

Next, we define the expected present value of fusion $EPV_{fus,\alpha}$ as the value of fusion $V_{fus,\alpha}$ adjusted by the success probability p_{ACP} and the non-fusion value V_{nofus} (details follow below), weighted by its complementary probability $(1 - p_{ACP})$:

$$EPV_{fus,\alpha} = \left[p_{ACP} * V_{fus,\alpha} + (1 - p_{ACP}) * V_{nofus}\right] \tag{2}$$

This valuation approach is based on the simple expected value formula for a single time step drawn conceptually from a binomial decision. We set $V_{nofus} = 0$, assuming that magnets and lasers

developed for fusion may not have a direct repurposing opportunity, which would limit potential returns if fusion fails to reach commercialization. When solving for p_{ACP}, we receive:

$$p_{ACP} = \left(\frac{EPV_{fus,\alpha}}{V_{fus,\alpha}}\right) \tag{3}$$

Thus, if we treat the expected present value of fusion as its cumulative discounted investments, the Anticipated Commercialization Probability (p_{ACP}) can be interpreted as how investors assess fusion's likelihood of realizing its value. A high fusion value, reflected in significant system savings potential, would justify substantial investments. If actual investments fall short of this potential, the ACP remains low. Conversely, if investments exceed the projected system savings, both the ACP and the expected fusion value may be overestimated.

As defined in Equation (1), the value of fusion $V_{fus,\alpha}$ is defined by the discounted sum of achieved energy system savings[14]. To calculate the latter, we conduct a scenario analysis of a cost-optimal energy system with fusion energy using the open source model PyPSA-Eur[23]. Its sector-coupled optimization allows us to evaluate the impact of fusion power on the total energy system, including vectors such as electricity, fuels, hydrogen, and other gases. Following the call for research by[15], we choose PyPSA-Eur with its high temporal and spatial granularity to enable more detailed modeling of Europe's interconnected energy system and account for regional differences in grid infrastructure and renewable resource availability. Specifically, our analysis employs a myopic optimization approach building on configurations from previous time steps with a 3-hour temporal resolution, covering the period from 2030 to 2100 across a 39-node network in Europe[24]. We examine various scenarios, including different fusion commercialization years (2035, 2050), overnight capital costs (low, base, high) — hypothetical capital costs reflecting investments as if the power plant had been built overnight —, a capacity constraint combining technology diffusion theory with annual build-out limits[19,20], and an analysis of fusion cogeneration. See Table 2 for an overview of scenario variables and Figure 1 for details on nomenclature. To reflect realistic system development, the optimization begins in 2030, ahead of fusion's availability in 2035. This ensures that the model first establishes an energy mix based on existing technologies, with fusion added only once it becomes a viable option.

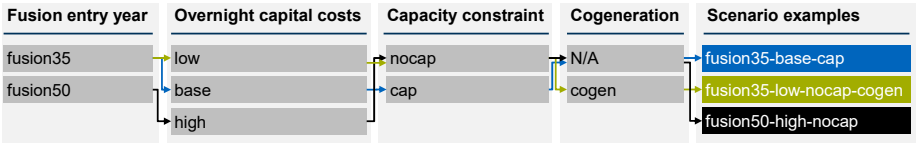

Figure 1: ***Overview of scenario parameters and structure of nomenclature.*** *We model a set of scenarios based on four parameters including fusion entry years (2035, 2050), overnight capital costs (low, base, high), a capacity constraint combining technology diffusion theory with annual build-out limits (nocap, cap), and an analysis of fusion cogeneration (cogen). (Own illustration)*

As for the $EPV_{fus,\alpha}$, we assess cumulative fusion investments by incorporating both public and private funding streams from 2010, reflecting the point at which private investments signaled

tangible commercialization prospects. To account for the time value of money, we introduce the Weighted Average Cost of Fusion (WACF), analogous to the weighted average cost of capital (WACC). This allows us to factor in the different return expectations for public (2% or 5% risk-free social discount rate as per[13,14,22,24]) and private (17% elevated return, see[25]) investments. We use historical public investment data from European countries, alongside global private-sector data. The latter is scaled based on its impact on the European energy system using Europe's share of the global electricity market. Our projections estimate EUR_{2020} 42 billion in discounted, cumulative public and private fusion investments in Europe by 2035 and EUR_{2020} 76 billion by 2050. Figure 2 illustrates the capital values in consideration and their relation to the base year 2030, accounting for the time value of money. Further, see section 4 Experimental Procedures to learn more about our modeling approach and assumptions.

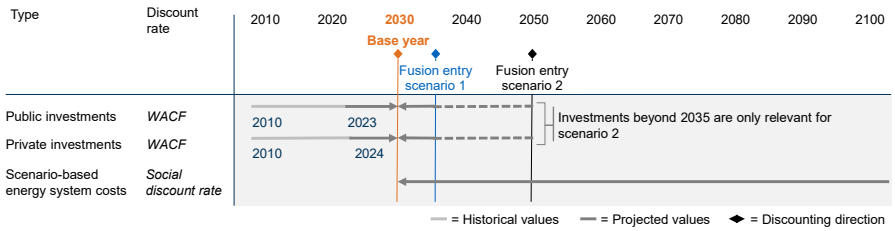

Figure 2: ***Capital flows and time value of money.*** *Overview of the investment categories and system savings assessed, with all values discounted to the 2030 base year using relevant rates. (Own illustration)*

In the following, we first examine the potential impact of fusion on the future energy system costs in subsection 2.1, focusing on its technical market share in terms of installed capacity and energy generation. This analysis sets the stage for evaluating the cost impact of fusion energy in subsection 2.2. Finally, we conclude by comparing energy system savings with investment levels to determine the implicitly expected probabilities for commercialization in subsection 2.3.

2.1. Contribution of fusion energy to the energy mix of the future

According to our optimization results, as shown in Figure 3, fusion deployment in Europe follows three distinct phases:

- **Diffusion-Phase** (2035-2050): Fusion grows in parallel with increasing electricity demand during the energy transition.
- **Replacement-Phase** (2050-2070): A second wave of fusion growth coincides with the end-of-life replacement of renewables installed during the pre-2040 high-growth phase. This shift is primarily driven by the phase-out of wind capacity, which loses competitiveness due to its comparatively lower learning rates relative to solar PV.
- **Saturation-Phase** (2070-2100): Fusion's relative advantage diminishes as cost reductions slow. The technology reaches a saturation point where fusion's learning rate unlocks new energy generation potential only under favorable cost trajectories.

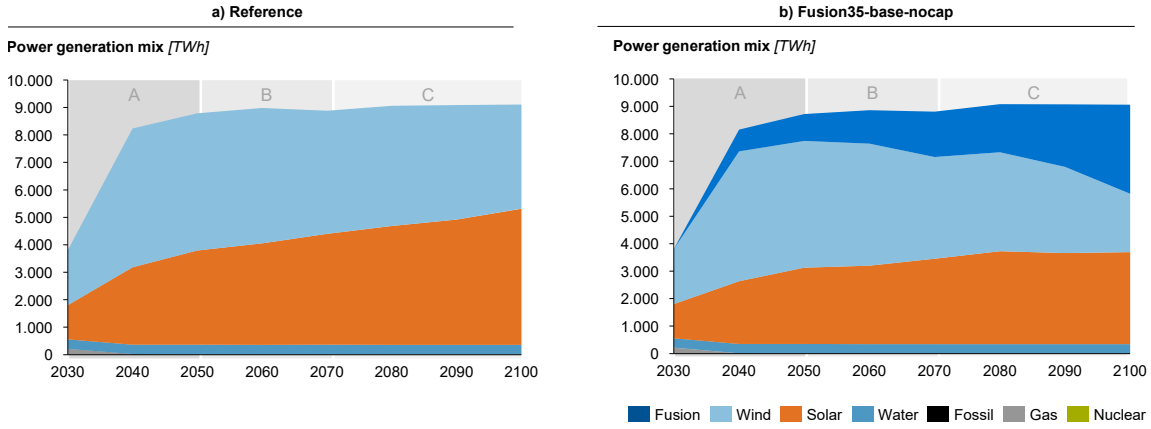

Figure 3: ***Evolution of Europe's energy generation mix with and without fusion.*** *Projected electricity generation by source from 2030 to 2100 for the reference scenario (a) and the unconstrained fusion scenario with a 2035 entry year (b). Fusion deployment follows three phases: A - initial diffusion with rising electricity demand, B - replacement of aging renewables (especially wind) post-2050, and C - a late saturation phase as cost advantages level off relative to solar PV, depending on scenario assumptions. Note: The reference scenario follows PyPSA-Eur assumptions extrapolated to 2100, as described in subsection 4.2. (Own illustration)*

Figure 4 compares how techno-economic and temporal factors shape fusion deployment trajectories across key scenarios. Overall, the results indicate that while delays in commercialization reduce near-term uptake, fusion's long-term potential remains robust under favorable cost conditions, provided rapid scaling is achievable once initial barriers are removed. This suggests that sustained cost reductions and industrial capacity expansion may be more decisive for fusion's eventual role than short-term demonstration milestones alone. However, this resilience does not extend to mid-century decarbonization goals, which critically depend on fusion becoming available in time to contribute meaningfully within the timeframe by 2050.

Capital costs emerge as the primary determinant of fusion's market share: at high cost levels, fusion remains economically marginal, contributing less than 1% of total capacity by the end of the century. In contrast, if fusion achieves competitive c, even moderate delays in deployment are outweighed, allowing installed capacity to exceed 800 GW and positioning fusion as a dominant baseload technology delivering up to three-quarters of total generation. Our results spanning from 10.6 to 42.8% capacity market share for a 22.5% OCC increase confirm the high sensitivity to capital cost assumptions, as discussed in previous literature. Consistent with Ref.[14,17,18], we find that fusion can make a notable contribution at competitive costs of <4,000 USD_{2020}/kW_{el} by 2100 (see Figure A.4 for an overview of market shares over OCCs in the literature). This cost level aligns well with the plans of the private fusion industry, highlighting its impact if successful[19]. However, while targeting low-cost designs from the outset may not always be feasible, designing fusion technology for scalability and learning will be crucial to achieving cost reductions and increasing its

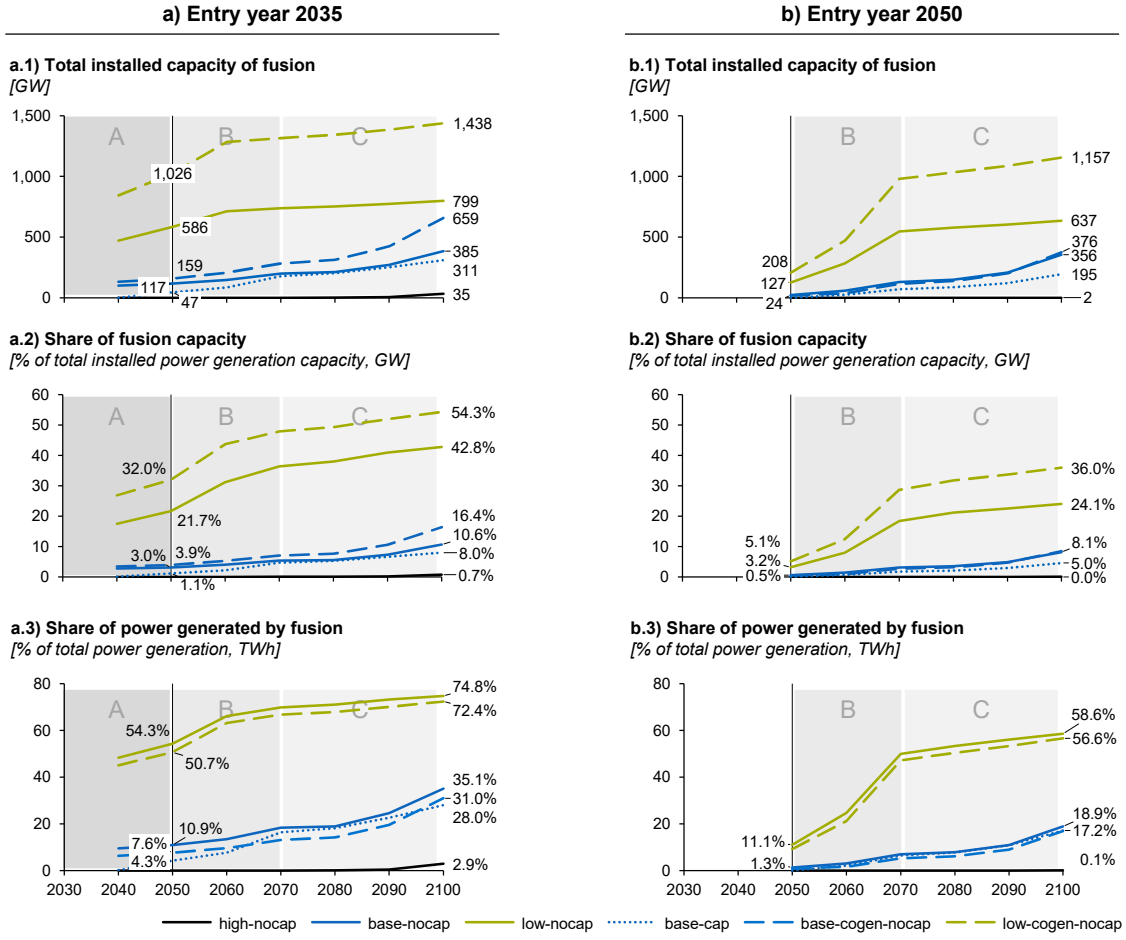

Figure 4: ***Projected fusion deployment trajectories in Europe.*** *Comparison of total installed fusion capacity (a.1, b.1), share of installed capacity (a.2, b.2), and share of electricity generation (a.3, b.3) under multiple cost and capacity scenarios for fusion entry in 2035 (a) and 2050 (b). Delays reduce long-term capacity only modestly, while capital costs and deployment constraints remain the dominant drivers of fusion's system contribution. Note: Graphs are partially overlapping, such as base-cogen-nocap and base-nocap for fusion entry in 2050. (Own illustration)*

contribution to the energy system.

The scenarios further illustrate how physical constraints on industrial capacity or manufacturing scale can become binding, limiting diffusion rates even when economic competitiveness is achieved. While the capacity constraint significantly limits deployment in the low-cost scenario, its impact is more moderate in the base case. This is because the constraint aligns closely with fusion's natural diffusion potential under moderate cost assumptions, resulting in only a limited reduction in installed capacity.

At the system level, renewables retain the largest share of installed capacity in almost all scenarios, accounting for more than half of the power system by 2100, with solar progressively overtaking wind as learning effects increase its cost advantage (see also Figure A.3 in the Supplementary Information). Fusion's main system effect is to reduce the total installed capacity required to meet demand. By offering high-capacity-factor baseload supply, fusion displaces low-capacity-factor renewables like solar. Solar energy, with an average capacity factor of <20%, requires approximately 5-6 times more installed capacity than fusion, while wind, with a capacity factor of <40%, requires 2-3 times more. As a result, with only a 10% installed capacity share, fusion can provide around 30% of energy generation by 2100 (see Figure 4 a.3 and b.3). By providing firm baseload power, fusion also reduces reliance on storage, demand-side flexibility, and grid expansion, thereby lowering overall system costs as discussed in the next section.

As expected, including heat provision through cogeneration significantly increases fusion's potential, doubling the market size to over 1,400 GW. Naturally, this comes at the expense of net electricity output per unit capacity decreasing overall power generation despite higher capacity shares. This finding underscores that sector coupling can significantly enhance fusion's system contribution, particularly in regions with existing or economically feasible district heating networks. However, this potential depends on robust safety standards and regulatory frameworks that allow fusion plants to be sited near heat demand centers.

In conclusion, these insights highlight that accelerating cost declines, resolving diffusion constraints, and enabling sector coupling are pivotal levers for realizing fusion's potential contribution to a resilient, low-carbon energy system. Comparisons with previous studies indicate that the projected market shares here lie at the conservative end of the literature range. This is partly because our regional scope is limited to Europe, where population and demand growth are moderate compared to high-growth regions such as Asia and parts of the Global South. Historical analogies, such as the rapid global diffusion of fission during the 1970s[26], suggest that fusion adoption could accelerate where strong demand growth persists and low-carbon baseload is scarce. Extending this modeling to high-growth economies would likely increase the estimated global market potential. For a granular assessment of our results compared to the existing body of literature, please refer to the Supplementary Information.

2.2. Fusion-enabled energy system cost savings

Building on the impact of fusion on the energy mix, we analyze the system cost savings resulting from changes in system configuration. We define the value of fusion $V_{fus,\alpha}$ as the discounted cumulative cost savings from the first year of fusion deployment (2035 or 2050) to the end of the

modeling period (2100), as outlined in Equation (2). We calculate present values for each 10-year period as the annuities of annual system costs, assuming a linear cost distribution provided by PyPSA's cumulative cost integral function, and discount these costs to the base year $t_0 = 2030$.

Cumulative system cost savings amount to approximately EUR_{2020} 253 billion by 2100 — about 3% of annual system costs — while under more favorable cost assumptions, savings rise nearly eightfold to almost EUR_{2020} 2 trillion (see Figure 5). Interestingly, absolute generation costs rise with increasing fusion shares, but this is offset by savings in other system verticals: The primary driver of savings is the near elimination of demand-side storage, including (home) batteries, electric vehicles for vehicle-to-grid, and thermal water tanks, followed by reductions in supply-side storage, demand costs, and grid-related expenses. This underscores a core insight: fusion's economic leverage stems less from cheap electricity per se and more from its ability to reshape the broader architecture of the electricity system. This system rationalization offsets the higher unit generation cost of fusion relative to renewables. The temporary dip in net savings observed around 2070 in the low-cost scenario reflects this dynamic: as older, cheaper solar PV reaches end-of-life, fusion takes its place at a higher cost, but this substitution lowers infrastructure and balancing costs further downstream, yielding net system gains by 2100.

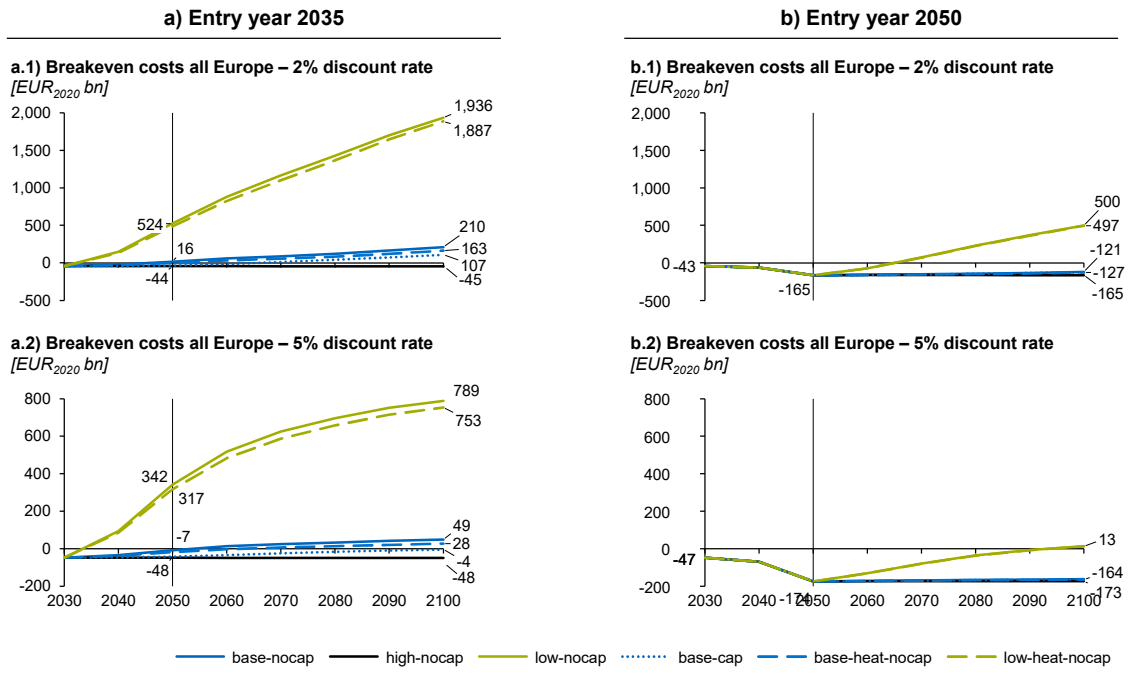

Figure 5: ***System cost savings enabled by fusion energy.*** *Cumulative discounted system savings relative to a scenario without fusion (a.1, b.1) and annual savings as a share of total system costs (a.2, b.2) for entry years 2035 (a) and 2050 (b). Savings arise mainly from reduced storage, grid, and flexibility costs, rather than lower generation costs. The sharp increase under unconstrained low-cost assumptions highlights the importance of capital cost trajectories and supply chain scale-up for unlocking fusion's full system value. (Own illustration)*

Despite the relatively modest impact of delayed fusion availability on market share, the effect on system cost savings is significant. Across scenarios, postponing deployment to 2050 nearly eliminates the financial benefits seen with an entry in 2035. This is because late savings contribute less to the discounted value, and no meaningful cost reductions can occur before 2050, as system configurations without fusion do not differ from the reference case.

Figure 6 further illustrates how fusion shapes regional cost dynamics. By providing geographically flexible firm capacity, fusion mitigates disparities in nodal system costs that arise from unequal distribution of renewable resources and infrastructure constraints. For example, without fusion, the UK faces substantially higher system costs than Germany due to its island status and limited interconnection options; fusion helps narrow this gap by reducing dependence on local renewables and expensive balancing capacity. By 2100, fusion adoption could reduce long-distance AC and DC grid capacity by 15–20% and hydrogen transmission capacity by up to 45%, redistributing investment needs across regions and lowering overall system complexity.

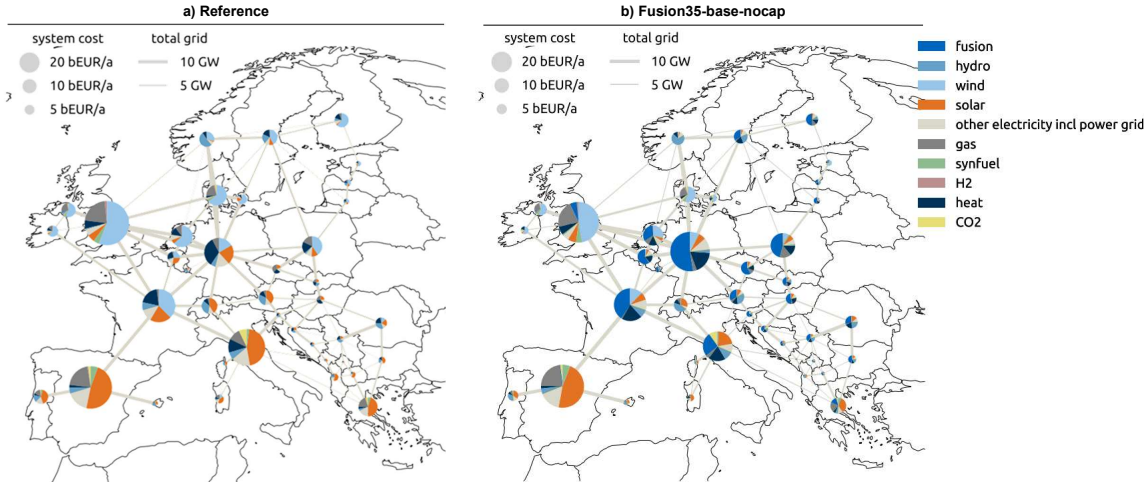

Figure 6: ***Regional distribution of annual system costs with and without fusion by 2100.*** *Modeled annual energy system costs by node for 2100 in a) the reference scenario without fusion and b) the unconstrained base fusion scenario with a 2035 entry. Fusion deployment reduces regional cost disparities by lowering reliance on long-distance grids and balancing renewable resource mismatches, with pronounced adoption in regions with limited domestic renewables. (Illustration modified from Ref.*[23,27]*)*

Benchmarking against prior global estimates suggests that Europe's system cost savings align well with expected global values[13,14]. A key factor shaping this valuation is the choice of social discount rate: applying a higher rate (5%[13,22] as opposed to 2%[14,24]) can halve the present value of cumulative savings by 2100. This highlights the importance of consistent economic assumptions when comparing fusion's potential contribution across studies and timescales.

2.3. Fusion energy Anticipated Commercialization Probability

In this section, we link the projected energy system cost savings with the investments observed for fusion, illustrating investors' perspective on whether and when these savings could be realized in practice. By comparing the expected present value of total private and public investments ($EPV_{fus,\alpha}$) with the cumulative system cost savings, we derive an Anticipated Commercialization Probability for each scenario. Current investment levels suggest that, for a 2035 market entry, investors implicitly assign a commercialization probability below 20% in most cases, regardless of the chosen social discount rate. This misalignment indicates that, despite high theoretical system benefits, the perceived probability of success remains low, or conversely, that actual investments fall short of the scale of the opportunity.

A complementary analysis of net system savings — calculated by subtracting the expected present value of fusion investments from cumulative system savings — shows that fusion reaches system breakeven within 5 to 15 years in most scenarios, even with higher discount rates (see Figure 7). This payback period extends to only 35 years, even when diffusion is constrained.

In contrast, if economic viability is challenged or market entry is delayed, this picture shifts fundamentally. Fusion becoming available only by 2050 sharply reduces the present value of late-stage savings, erasing net system benefits except in the most optimistic cost cases. This highlights a crucial insight: early deployment and competitive capital costs are not only climate imperatives but also critical for achieving economic returns within relevant investment horizons until 2100. Under late-entry scenarios, breakeven timelines extend beyond 2100, and ACP estimates approach 100%, reflecting that at current investment levels, investors expect fusion's success by 2050 at the latest. Yet, we argue that this confidence depends heavily on visible progress toward a 2035 entry; if milestones are missed, trust in commercialization could erode, and funding flows may weaken in subsequent decades.

These findings reveal a paradoxical cycle: despite an enormous hypothetical market potential, investment remains low, in part due to uncertainty about the success of commercialization. As a result, this lack of investment may itself lower the probability of proving success. While the ACP serves as an estimate of investors' expectations regarding the technological success of fusion energy, it should not be mistaken for an indicator of actual technical feasibility. Financial sentiment and engineering reality are interdependent but not interchangeable; robust technical certainty will only emerge as the first prototypes are built and tested.

3. Conclusion and implications

Our findings suggest that fusion energy could fundamentally reshape Europe's future energy system. Under conditions of high cost competitiveness and unconstrained deployment, fusion may account for up to 42.8% of installed generation capacity by 2100. This level of integration reduces the need for large-scale storage, extensive grid expansion, and renewable overcapacity, thereby significantly lowering overall energy system costs. The benefits could be further amplified if fusion is able to supply heat, as illustrated in our cogeneration scenario, which nearly doubles fusion's market share in terms of installed capacity. Realizing this potential, however, depends on the continuation of

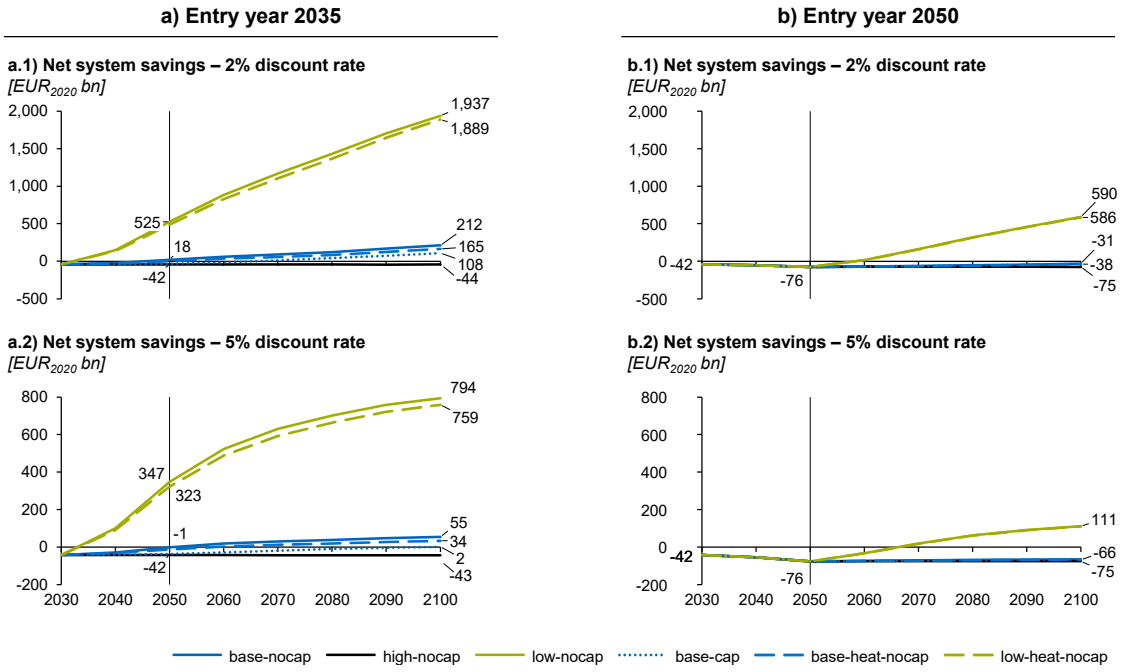

Figure 7: ***Breakeven analysis for fusion under varying scenarios and discount rates.*** *Projected net system cost balance of fusion deployment relative to cumulative investments for a 2% discount rate (a.1, b.1) and a 5% rate (a.2, b.2) for fusion entry in 2035 (a) and 2050 (b). Faster breakeven occurs under favorable cost and early deployment assumptions, while high costs and delays postpone or prevent positive returns within this century. (Own illustration)*

current regulatory initiatives[28,29] and the validation of key assumptions regarding fusion's inherent safety and minimal radiative impact[19]. Beyond cost and capacity benefits, high fusion penetration provides strategic value for Europe's energy sovereignty. As a geographically flexible technology, fusion can help align local supply and demand more effectively, enhancing system resilience. Additionally, by enabling local production of hydrogen and synthetic fuels, it could reduce import dependency and serve as a cornerstone of Europe's long-term energy security.

A key insight from our analysis is that fusion's impact is shaped far more by its cost and deployment dynamics than by the year of its commercialization. From a generation mix perspective, delays in deployment by 15 years are less critical than the ability to scale rapidly and efficiently once fusion becomes technically viable. However, the system value diminishes significantly with delayed availability, and unlike the broader system, private sector developers may lack the financial resilience to absorb the additional capital and opportunity costs of prolonged timelines. To realize fusion's full value, both public and private actors should therefore prioritize modular, replicable designs that can be standardized to lower costs and constructed with minimal regulatory friction[30]. Lessons from nuclear fission show that construction time, financing risk, and regulatory fragmentation are among the biggest cost drivers[31–33]. Therefore, deployment strategies should emphasize modular reactor designs with factory-based production, streamlined licensing procedures via internationally harmonized standards, and targeted incentives that support early-stage deployment and de-risk private investment[34]. Milestone-based policy frameworks — with predefined triggers for investment, siting, or infrastructure development — could help reduce uncertainty and facilitate coordinated action across governments, industry, and utilities.

Finally, relative to its estimated societal value as defined by fusion's potentially large system-level returns, current investment levels remain low - likely reflecting persistent skepticism about its successful commercialization. Our analysis shows that breakeven can occur within 5 to 15 years after deployment, yet the implied Anticipated Commercialization Probability remains below 20%. While this metric serves as a proxy for investor expectations regarding fusion's success under uncertainty, it should not be interpreted as an indicator of actual technical feasibility. These relatively low expectations may reflect an adequate accounting of uncertainty - or they may reinforce a classic high-risk/high-reward paradox: the perception of risk drives underinvestment, which in turn lowers the probability of success - a self-fulfilling cycle. Whether justified or not, this cycle illustrates how financial signals can shape - and potentially constrain - the trajectory of deep technology development.

Within this study, we abstract from technological distinctions between magnetic and inertial confinement fusion and from respective operational details. Given the comparable cost expectations and ongoing uncertainties, this simplification is reasonable at the current stage[3,14]. However, future studies should explore more granular techno-economic pathways across different fusion concepts. Additional limitations stem from the PyPSA-Eur framework, most notably the lack of differentiation between technical and economic lifetimes. A single lifetime parameter is used to annualize capital costs and determine asset decommissioning, which results, for example, in idle nuclear capacity in France due to high capital costs. A more nuanced representation could better reflect real-world conditions. Despite these caveats, our results indicate that the scale of potential system savings warrants reassessment of funding mechanisms and energy system planning. Over-reliance

on technologies offering only incremental improvements may lock in high system costs. This path dependency risks undermining the system cost advantage offered by transformative solutions such as fusion.

4. Experimental Procedures

4.1. Resource availability

Lead contact Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Sophia A. E. Spitzer (sophia.spitzer@tum.de).

Materials availability This study did not generate new unique materials.

Data and code availability Data for this paper, as well as the code used for analyses, are available at https://github.com/antbau/pypsa-eur-fus.

4.2. Energy system optimization

PyPSA-Eur model setup We employ the open-source PyPSA-Eur model (release v0.13.0[23]) to simulate a sector-integrated, long-term optimal European energy system. This model provides high temporal and spatial resolution, operating with 3-hourly timesteps over an entire year, including a network of 39 nodes representative of the main regions in Europe[24]. According to a sensitivity analysis by[27] and supported by the broader energy system optimization literature[35], this granularity provides a reasonable balance between computational load and accuracy. To analyze the system's evolution, we use a myopic approach in 10-year intervals from 2030 to 2100, where each interval aims to minimize total system costs within a given CO_2 constraint. Technologies introduced in previous periods remain active in the system until they reach the end of their expected lifespan. Unlike a perfect foresight approach, this method generally results in higher costs but more accurately mirrors the short-term focus of policy and investment decisions, with less sensitivity to the social discount rate[24]. Conceptually, capacity expansion planning considers how increasing deployment of energy technologies impacts their value, reaching a balanced state where the cost of adding more capacity for each non-restricted technology equals its benefit to the system. For emerging energy technologies like fusion, accurately forecasting market potential and cost targets requires accounting for these complex interactions in both the short and long term[3].

The model is described in detail in[24,36–38]. In the following, we provide a brief overview structured along the main vectors used in PyPSA-Eur: electricity, heat, hydrogen, biomass, methane, oil, and CO_2 (see also Figure 8):

- **Electricity** generation options include solar, onshore/offshore wind, hydroelectricity, gas and hydrogen turbines (both open and combined cycle turbines), coal, lignite, nuclear, and combined heat and power (CHP) units with and without CCS. By default, PyPSA-Eur treats

coal, lignite, and nuclear fission as non-extendable technologies, phasing them out by mid-century. In this study, we relax this constraint for nuclear fission, allowing it to be extendable without capacity limits throughout the modeling period. Renewable time series and maximum capacity estimates incorporate geographic and climatic data as well as technical constraints based on land use and conservation areas in a cluster network. To manage computing demand for grid optimization, this network is aggregated to 39 nodes. PyPSA-Eur uses a historical time series of hourly electricity load[39], adjusting for the separately modeled electrified heating, transport, and industry demand to avoid double-counting. Storage is managed through batteries, hydrogen, and pumped hydro storage. Both transmission and distribution power grids are taken into account, though at different levels of detail: The transmission grid connects high-voltage networks across Europe and is optimized for capacity and routing between the 39 clustered nodes, considering physical constraints and n-1 reliability standards[37]. Transmission line capacities are adjusted to allow efficient power flows between regions, which is essential for balancing variable renewable generation. In contrast, the distribution grid is simplified, focusing only on total capacity down to the low-voltage level, where technologies like rooftop solar, home batteries, and heat pumps connect. Distribution grid expansion is modeled only when local demand outpaces generation, ensuring that upgrades are cost-efficient and avoid unnecessary infrastructure expansion.

- Annual **heating** demand data (from[40]) is distributed based on population density and so-called heating degree days defined by the delta between ambient and threshold temperature of 15°C. Building retrofitting is assumed to gradually reduce space heating demand as reflected by an exogenously defined factor. In densely populated areas, district heating supplies 60% of heating needs, using a mix of heat pumps, resistive heaters, gas boilers, and CHP. Individual heat pumps or gas boilers cover non-district-heated areas. Heat pumps' coefficient of performance varies with temperature, accounting for seasonal efficiency changes. Thermal energy can be stored in water tanks.
- **Hydrogen** demand serves industrial ammonia production, steelmaking, and transport directly (road, shipping) or via synthetic fuels (aviation, shipping). Hydrogen is produced via steam methane reforming, with and without carbon capture, or electrolysis. It may be stored in steel tanks or salt caverns, while a greenfield hydrogen network connects nodes along existing gas pipelines or transmission lines, where cost-effective. The model optimizes hydrogen production methods based on costs and CO_2 constraints.
- **Biomass** sources include agricultural residues, forestry waste, and biodegradable municipal waste. Biomass is primarily used for CHP, supplying medium-temperature heat in district heating or industry, while manure and sludge are processed into biogas and upgraded to biomethane. Biomass demand in each country is matched to domestic potentials[41], limiting imports from outside of Europe. The model avoids energy crops and primary wood due to competing use cases, but rather emphasizes feedstocks such as residues and wastes.
- **Methane** demand includes individual and large-scale boilers and CHP for industrial sectors such as cement or parts of aluminum production. Methane supply options include fossil methane, synthetic methane, biogas, or combined methanation. Existing gas networks support free methane transport between countries, assuming demand will be too low to cause

bottlenecks.

- **Oil** demand covers non-electrified land transport, aviation, and chemical feedstocks. Synthetic oil is produced using the Fischer-Tropsch process with captured CO_2 and hydrogen. This process also supplies waste heat for district heating. Fossil and synthetic oil proportions are optimized based on technology costs and CO_2 limits.
- The model includes **carbon** capture from industry, steam methane reforming, methane or biomass-based processes, and CHP. Captured CO_2 is used for synthetic fuel production or storage. Direct air capture (DAC) also enables negative emissions. CO_2 transport is unrestricted, but storage is limited to a conservative 200 $MtCO_2$ per year for Europe[24].

PyPSA-Eur employs a brownfield approach to represent Europe's existing energy infrastructure[37]. It incorporates data on installed transmission lines, capacities for conventional power plants (e.g., coal, nuclear, gas), and renewable sources like wind and solar, based on 2020 capacity data. Decommissioning schedules reflect each technology's typical lifespan, removing aging assets progressively. This setup enables the model to evaluate decarbonization strategies on top of the current infrastructure, ensuring that the transformation aligns with real-world constraints and operational dynamics of Europe's energy system.

Each technology modeled in PyPSA-Eur is characterized by a set of techno-economic attributes: **Capital costs** reflect OCCs per unit of installed capacity [in EUR_{2020}/kW_{el} or EUR_{2020}/kW_{CH4}]. **Fixed operating and maintenance (FOM)** costs do not scale with technology utilization and are given by an annual percentage of the investment costs, whereas **variable operating and maintenance (VOM)** costs scale with consumption [EUR_{2020}/MWh]. Following the assumptions in PyPSA-Eur, each technology's total investment is annualized using the expected lifetime [years] and a financial discount rate of 7%. Individual, decentralized assets, such as rooftop PV or domestic water tanks, are assigned a lower rate of 4% to reflect the typically reduced return expectations of private households[36]. Additionally, a social discount rate is used to balance short-term and long-term costs in transition pathways. Two values are adopted from the literature: 2%, in line with historical growth averages (1.6%) in the European Union and United States Treasury yields[14,24] and 5%[13,22].

In terms of technological parameters, the efficiency of a technology gives the ratio between the useful energy output and the input. Operational parameters for dispatchable power plants include ramping constraints, start-up costs, and minimum part-load levels. Minimum up- and downtimes are applied only to non-extendable plants in order to preserve linearity. Additionally, storage systems are constrained by maximum charging and discharging rates. A back-pressure coefficient and an electricity loss coefficient are modeled as well. The CO_2 intensity tracks carbon emissions measured in [tCO_2/MWh_{th}].

A detailed overview of the techno-economic data and the mathematical formulation can be found in Ref.[24]. All cost assumptions until 2050 from the Python repository technology-data[42] are inflation-adjusted to 2020.

Model projection to 2100 We extend the PyPSA-Eur model's time horizon from 2050 to 2100. As the energy transition matures and the system approaches saturation, we expect technological and economic trends in Europe to stabilize. This assumption aligns with the 'Energy and Environmental

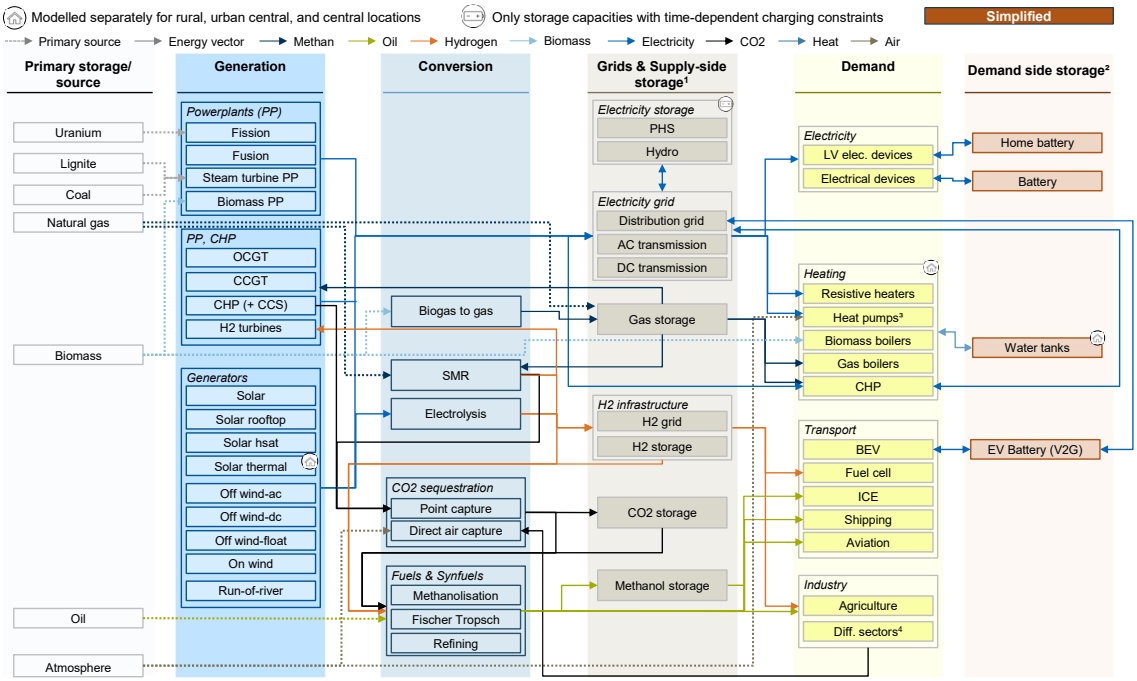

Figure 8: ***Simplified overview of technologies included in the PyPSA-Eur model.*** *Schematic representation of the sector-coupled energy system as modeled in PyPSA-Eur, covering electricity generation, conversion, storage, grid infrastructure, CO_2 capture and storage, and end-use sectors. This provides the framework for simulating fusion's integration into a future European energy system. (Own illustration based on Ref.[24])*

[1] *Supply-side storage includes large-scale, centralized storage primarily interacting with energy supply (not visualized).*

[2] *Demand-side storage refers to storage located close to demand, responding to user needs and often integrated into homes, businesses, or electric vehicles.*

[3] *Heat pumps comprise air and ground heat pumps.*

[4] *Sectors include Steel and Metals Industry; Chemicals and Pharmaceuticals; Construction Materials; Pulp, Paper, and Printing; Food and Beverage; Textiles and Wood Products; Manufacturing and Machinery.*

[5] *Uncaptured CO_2 emissions not visualized.*

Kuznets Curve' hypothesis, which suggests that once developed countries reach a certain economic threshold, growth decouples from energy consumption and CO_2 emissions due to efficiency gains and structural shifts toward service-based economies[43,44]. To reflect this stabilization, several key assumptions are made:

- Once carbon neutrality is achieved by 2050, no additional changes in energy demand are assumed, in line with PyPSA-Eur's default setting[23]. At this point, major energy transitions, such as the shift to green steel production and fuel transitions in the transport sector, are considered fully realized. Consequently, industrial production and energy demand remain stable at 2050 levels.
- Geo-physical framework conditions, including biomass potential, district heating potential, and CO_2 sequestration capacities, are also held constant at their 2050 levels.
- Technology cost developments are projected using learning curves for those technologies that have not yet reached a saturated phase by 2050[45]. The saturation threshold is defined as a cost degression of less than 5% over the last decade from 2040 to 2050. Based on this criterion, 186 technologies are classified as saturated, while 56 technologies continue to follow learning curves. A list of technologies with learning curves is provided in subsection A.1. To project costs beyond 2050 and incorporate fusion energy costs, the model's automatic cost retrieval is deactivated, and cost files are manually adjusted via the resource folder in PyPSA-Eur. Technology cost trajectories until 2050 are fitted using PyPSA-Eur's cost assumptions, sourced from the Danish Energy Agency's Technology Catalogues[46] and extended to 2100. Example cost curves are provided in Figure A.1 in the Supplementary Information.

Incorporating fusion power plants as energy links Consistent with the modeling of thermal power plants in PyPSA-Eur, fusion power plants were incorporated into the energy link portfolio, assuming no geographical constraints and maintaining resolution at the nodal level. In PyPSA-Eur, links act as energy generators with several input and output connections so that they can be connected to multiple buses, e.g., fuel input and output to the electricity grid, CO_2 grid, and/or heat grid. We determine the techno-economic parameters through a statistical analysis of assumptions from existing literature (see the final values summarized in Figure 9). The chosen OCCs align with median values of low, medium, and high cost assumptions found in recent studies. Fixed and variable operating costs are set at the median range as well (average of low and high means). The financial discount rate is set at 7%, consistent with rates applied to other large, centralized technologies in PyPSA-Eur. Building on learning effects observed in the fission industry, we adopt a conservative yet progressive cost reduction model. While early nuclear fission saw cost reductions of -5% to -15%[33], these were eventually reversed due to factors such as technological complexity, regulatory fragmentation, and project management challenges[31–33]. However, South Korea achieved consistent learning, with cost reductions of -25% in the first phase from 1972 to 1993 and -13% in the second phase from 1989 to 2008[33]. We base our assumption on the latter, projecting a -0.7% annual cost degression, which can be considered conservative given fusion's potential advantage in regulatory terms. Our approach provides a more granular perspective than the stepwise cost reductions commonly assumed in existing literature[17,19]. We assume cost degression begins with fusion's availability, as shown in Figure A.2 in the Supplementary Information.

	Overnight capital costs [USD_{2020}/ kW_{el}]	Fixed costs [% p.a. of OCC]	Variable costs [USD_{2020}/ MWh]	Lifetime [years]	Discount rate [%]
PyPSA	**3,984 — 5900 — 8,415**	**1.6%**	**6.8**	**40**	**7.0%**
25% Quartile	3,399 — 5,362	0.8% — 1.3%	1.8 — 4.2	40	5.0%
Median	3,984 — 5900 — 8,415	1.2% — 1.9%	5.9 — 7.8	40	5.0%
75% Quartile	5,249 — 8,713	2.4%	7.8 — 10.4	45	7.5%

Figure 9: ***Statistical assessment of techno-economic assumptions.*** *Fusion assumptions derived from median OCCs, fixed, and variable operating costs as provided by literature[3,12,13,15–17,19,21,22]. USD values depicted for comparability with literature; conversion to EUR at average 2024 conversion rate[47]. Discount rate refers to financial discount rate used for annualization of capital costs. Grey shades highlight median range. (Own illustration)*

Assuming fusion power plants can supply industrial heat[4,48], fusion could play a key role in sector coupling, expanding its market potential. Since heat cannot be efficiently transported over long distances, proximity to residential and industrial demand centers is essential. If fusion is regulated separately from fission, as seen in the UK and U.S.[28,29], it could be located closer to these heat demand hubs. For this analysis, we model a cogeneration case[49], assuming a 4% efficiency gain for a 60% power plant efficiency[18] from providing low-temperature heat at 80°C for district heating.

Scenario development To deal with uncertainty, we model a set of scenarios S with the three most influential scenario variables s_i according to our literature review (see summary in Table 2): We model two fusion entry years $s1 \in \{2035, 2050\}$, following the academic consensus that the year of fusion availability significantly influences its impact[13,14]. We choose 2035 based on the more progressive estimations[3,19] and the proposed timelines by the private industry[2], while 2050 follows the more conservative projections from the remaining references (see Table 1). OCCs vary as part of $s2 \in \{low, base, high\}$. The baseline scenario is set at 5,900 USD_{2020}/kW_{el}, converted to 5,424 EUR_{2020}/kW_{el} using the 2024 average EUR/USD exchange rate. This value represents the mean of the medium-cost assumptions across all analyzed publications. Similarly, the low-cost scenario (3,984 USD_{2020}/kW_{el}; 3,663 EUR_{2020}/kW_{el}) and high-cost scenario (8,415 USD_{2020}/kW_{el}; 7,737 EUR_{2020}/kW_{el}) reflect the average values of the respective low and high-cost estimates.

We incorporate a capacity expansion constraint for fusion energy based on historical technology growth patterns, using a framework inspired by[20] and extended in[19]. Initially designed to analyze global diffusion patterns, we modify this approach for Europe, as its development of other energy technologies reflects global trends (see Figure 10). This may be attributed to the strong connection between regional and global developments[26].

At the outset of a new technology, a phase of learning and capacity building precedes large-scale deployment. This period of exponential growth establishes a comprehensive supply chain for spe-

Table 2: ***Overview of scenario variables and parameter values.*** *Fusion deployment scenarios vary by entry year (s1), overnight capital cost (s2), annual capacity constraint (s3), and co-generation option (s4).*

s1: Fusion entry year	**s2: OCC** $[EUR/kW_{el}]$		**s3: Capacity constraint**		**s4: Co-generation**
2035	low	3,663	nocap	No constraint	Cogen
2050	base	5,424	cap	10 GW p.a.	
	high	7,737			

cialized materials such as advanced superconductors and high-performance lasers, refines intricate production processes, and trains a highly skilled workforce[20]. However, unlike previous studies, we argue that saturated capacity should not be exogenously defined, as this remains arbitrary. Instead, we propose a bottom-up S-curve derivation, using assumptions on first fusion reactors for the exponential phase[19] and historical nuclear fission build rates[50] for the linear phase. The saturation level follows naturally from power plant lifetimes, ensuring steady capacity growth while preventing unsustainable acceleration from continuous exponential expansion[20].

For the exponential growth phase, we assume a doubling time of 1.43 years, the fastest historical rate observed in solar technology[19]. While this may seem ambitious given fusion's technological complexity and anticipated construction timelines, previous analyses demonstrate that national circumstances often drive adoption rates as significantly as the technology itself[26]: A relevant historical parallel is Western Europe's nuclear fission expansion in the 1980s, where the energy crisis of the 1970s spurred an unprecedented increase in electricity generation capacity. Similarly, climate change urgency and policy-driven incentives could catalyze substantial investments and rapid advancements in fusion energy once the technology reaches maturity.

For the linear expansion phase, we rely on the historical diffusion of nuclear fission in Europe to estimate a suitable annual capacity addition rate. The slope of the linear phase corresponds to an average of 9.8 GW of new installations per year (see Figure 10). Given the higher complexity and safety requirements of fission compared to fusion, this assumption may even be conservative. Notably, this aligns with previous projections that 100 fusion plants at 1 GW each would need to be deployed within a decade to reach the linear phase[20]. This could be roughly equivalent to 10 GW in Europe, given its current 14% share of global electricity demand[51].

To bridge the exponential and linear phases, we assume first commercial fusion power plants will have a net output of around 200 MW, in line with private industry targets[52]. With this starting capacity and a 1.43-year doubling time, it would take 10 years to reach the linear growth rate of 9.8 GW annually, providing a well-grounded capacity expansion constraint. Figure 10 visualizes these assumptions.

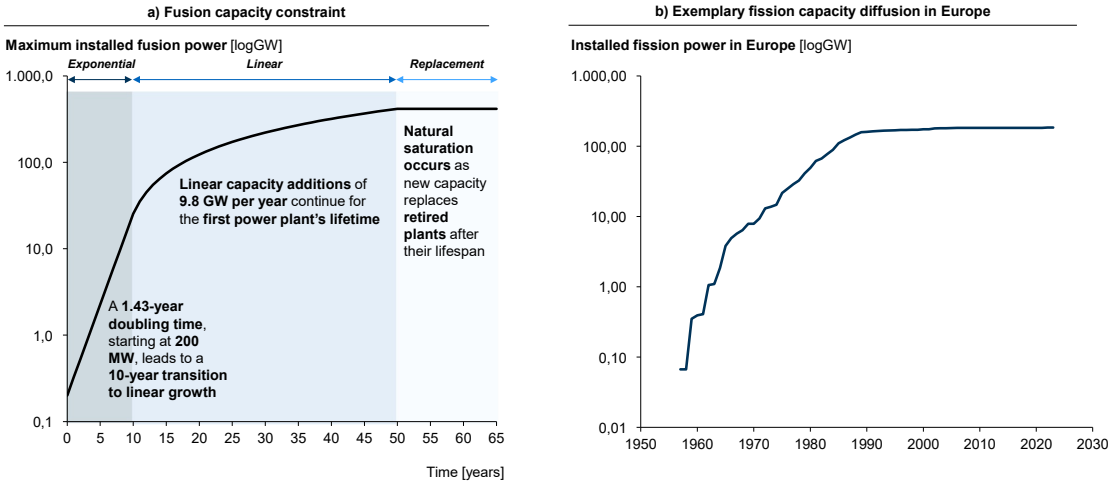

Figure 10: ***S-shaped fusion energy diffusion curve.*** *a) Schematic illustration of the expected exponential growth phase, assuming a 1.43-year doubling time over a 10-year period, transitioning to a linear build-out at 9.8 GW annual capacity addition and reaching saturation after one plant lifetime*[19,20,50]*. b) Historical fission capacity build-out in Europe shown for comparison*[50]*. (Own illustration)*

4.3. Fusion investment projection

To assess the probability of successful fusion commercialization, we calculate the expected present value of fusion $EPV_{fus,\alpha}$ based on historical and projected fusion investments. Public R&D investment in fusion dates back to 1974[53], primarily focused on basic science rather than commercial deployment. As the technology has yet to reach technical maturity, much of this early funding can be regarded as sunk cost from a commercialization perspective. In contrast, private-sector investment began in the early 2010s[9,54–56], signaling the emergence of explicit return expectations among private stakeholders. We argue that this development marks an inflection point, after which both public and private funding can be interpreted as increasingly directed towards commercializing fusion energy rather than advancing basic science alone.

To estimate cumulative fusion investments I_{total} while accounting for different return expectations, we discount each funding stream by an appropriate rate. Public investments I_{public} can be discounted using a risk-free social discount rate. We consider two cases in line with the energy system modeling: 2%[14,36] and 5%[13,22]. Private investors, however, expect higher returns r_p to compensate for the elevated risk associated with their investments $I_{private}$. An analysis of 115 European deep-tech funds — investing in research-intensive technologies with long lead times and high capital requirements similar to fusion energy — revealed an average internal return rate of 17%[25], which we adopt for this analysis. Hence, we introduce the Weighted Average Cost of Fusion (WACF), a metric analogous to the weighted average cost of capital (WACC) but tailored to the fusion context. Its purpose is to represent the combined return expectation of public and private investors, weighted to the respective investment share.

$$WACF = r_s * \frac{I_{public}}{I_{total}} + r_p * \frac{I_{private}}{I_{total}} \tag{4}$$

We then calculate the expected present value of cumulative investments up to the year of fusion market entry, depending on the respective scenario (scenario variable s_1) and discounted to the base year t_0.

$$EPV_{fus,\alpha} = \sum_{t=t_0}^{T_{s1}} (I_{private,t} + I_{public,t}) * (1 + WACF)^{-(T_{s1}-t0)} \tag{5}$$

We use historical data from 29 OECD countries and the European Union, covering public fusion R&D funding from 2010 to 2022, sourced from the iLibrary database from the Organization for Economic Cooperation and Development (OECD), part of the International Energy Agency (IEA) Energy Technology R&D Statistics[53]. For completeness, we supplement this with additional sources to fill regional gaps across 22 European countries and the EU[57–60]. By 2022, these countries accounted for 37% of total public investment, with Japan and the United States providing nearly all remaining contributions. Future public investment is extrapolated using a three-year moving average compound annual growth rate (CAGR) of the cumulative sum from 2019–2022. All values are converted to 2020 Euros[47].

Due to variations in both temporal scope and total investment figures across sources, private-sector investments were averaged across multiple relevant press articles[9,54–56,61]. Ref.[61] was supplemented by personal communication[62]. As of 2023, EUR_{2020} 5.8 billion has been invested in private fusion startups, with the majority directed to the U.S., driven largely by a single investment round of EUR_{2020} 1.6 billion by the U.S. startup Commonwealth Fusion Systems[63]. Two North American startups alone account for EUR_{2020} 2.6 billion, significantly distorting the private investment landscape[9]. While these investments are geographically spread, their global spillover effects remain relevant to European energy systems. Consequently, we include private capital flows in our analysis, projecting them using a three-year moving average CAGR of the cumulative sum from 2021 to 2024. To connect the impact of global investments to the European energy system, we scale the global investments by Europe's share of the global electricity system, which stands at 14%[51].

Using this framework, we estimate cumulative public fusion investments in Europe and private investments globally of approximately EUR_{2020} 41 billion by 2035 and EUR_{2020} 76 billion by 2050. The temporal development of the investments by source, as well as the WACF for the case of a 2% social discount rate, is given in Figure 11.

All currencies in this work are converted to EUR using the respective average annual exchange rates from the European Central Bank[47]. Additionally, inflation adjustments to 2020 are made based on historical inflation rates[64].

5. Declaration of authorship

Conceptualization, methodology, formal analysis, data curation, visualization, writing (original draft, review and editing), Sophia A. E. Spitzer; methodology, formal analysis, data curation, software, visualization, writing (original draft), Katja Pelzer; formal analysis, data curation, software,

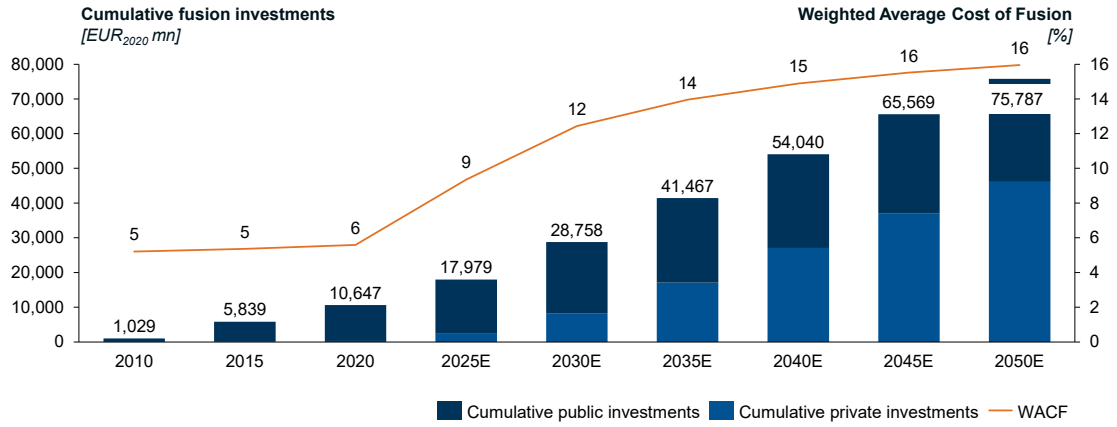

Figure 11: ***Projected fusion investments and implied financing costs in Europe.*** *Private and public fusion investments over time (left axis) and the corresponding discount-rate-weighted average cost of capital WACF, reflecting differing return expectations for public (2%) and private (17%) funding. (Own illustration)*

visualization, Anton Bauer; Conceptualization, writing (original draft, review and editing), Maximilian J. Blaschke

6. Declaration of interests

The author Sophia A. E. Spitzer is employed by Marvel Fusion, a private fusion company. This affiliation has not influenced the research design, analysis, or conclusions of this study. All views expressed are those of the author and do not necessarily reflect those of the employer.

References

[1] Armstrong, R. C., Whyte, D. G. & Field Randall. The Role of Fusion Energy in a Decarbonized Electricity System: A report from the MIT Energy Initiative in collabration with the MIT Plasma Science and Fusion Center (2024). URL `https://energy.mit.edu/news/mit-energy-initiative-releases-new-report-examining-potential-of-fusion-in-future-power-systems/`.

[2] Takeda, S., Keeley, A. R. & Managi, S. How Many Years Away is Fusion Energy? A Review. *Journal of Fusion Energy* **42** (2023).

[3] Schwartz, J. A., Ricks, W., Kolemen, E. & Jenkins, J. D. The value of fusion energy to a decarbonized United States electric grid. *Joule* **7**, 675–699 (2023).

[4] Nicholas, T. *et al.* Re-examining the role of nuclear fusion in a renewables-based energy mix. *Energy Policy* **149**, 112043 (2021).

[5] Takeda, S. & Pearson, R. Nuclear Fusion Power Plants. In Taner, T. (ed.) *Power Plants in the Industry* (IntechOpen, 2019).

[6] Ball, P. The chase for fusion energy. *Nature* (2021). URL `https://www.nature.com/immersive/d41586-021-03401-w/index.html`.

[7] Zylstra, A. B. *et al.* Burning plasma achieved in inertial fusion. *Nature* **601**, 542–548 (2022).

[8] Gibney, E. Nuclear-fusion reactor smashes energy record. *Nature* **602**, 371 (2022).

[9] Fusion Industry Association. The global fusion industry in 2023: Fusion Companies Survey by the Fusion Industry Association (2024). URL `https://www.fusionindustryassociation.org/wp-content/uploads/2023/07/FIA%E2%80%932023-FINAL.pdf`.

[10] Sepulveda, N. A., Jenkins, J. D., de Sisternes, F. J. & Lester, R. K. The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation. *Joule* **2**, 2403–2420 (2018).

[11] DeCarolis, J. *et al.* Formalizing best practice for energy system optimization modelling. *Applied Energy* **194**, 184–198 (2017).

[12] Gi, K., Sano, F., Akimoto, K., Hiwatari, R. & Tobita, K. Potential contribution of fusion power generation to low-carbon development under the Paris Agreement and associated uncertainties. *Energy Strategy Reviews* **27**, 100432 (2020).

[13] Tokimatsu, K., Fujino, J., Konishi, S., Ogawa, Y. & Yamaji, K. Role of nuclear fusion in future energy systems and the environment under future uncertainties. *Energy Policy* **31**, 775–797 (2003).

[14] Turnbull, D., Glaser, A. & Goldston, R. J. Investigating the value of fusion energy using the Global Change Assessment Model. *Energy Economics* **51**, 346–353 (2015).

[15] Müller, I. M. *et al.* Analysis of technical and economic parameters of fusion power plants in future power systems. *Fusion Engineering and Design* **146**, 1820–1823 (2019).

[16] Bustreo, C., Giuliani, U., Maggio, D. & Zollino, G. How fusion power can contribute to a fully decarbonized European power mix after 2050. *Fusion Engineering and Design* **146**, 2189–2193 (2019).

[17] Cabal, H. *et al.* Fusion power in a future low carbon global electricity system. *Energy Strategy Reviews* **15**, 1–8 (2017).

[18] Han, W. E. & Ward, D. J. Revised assessments of the economics of fusion power. *Fusion Engineering and Design* **84**, 895–898 (2009).

[19] Lerede, D., Nicoli, M., Savoldi, L. & Trotta, A. Analysis of the possible contribution of different nuclear fusion technologies to the global energy transition. *Energy Strategy Reviews* **49**, 101144 (2023).

[20] Lopes Cardozo, N. J., Lange, A. G. G. & Kramer, G. J. Fusion: Expensive and Taking Forever? *Journal of Fusion Energy* **35**, 94–101 (2016).

[21] Gnansounou, E. & Bednyagin, D. Multi-Regional Long-Term Electricity Supply Scenarios with Fusion. *Fusion Science and Technology* **52**, 388–393 (2007).

[22] Vaillancourt, K., Labriet, M., Loulou, R. & Waaub, J.-P. The role of nuclear energy in long-term climate scenarios: An analysis with the World-TIMES model. *Energy Policy* **36**, 2296–2307 (2008).

[23] Brown, T. *et al.* PyPSA-Eur: An open sector-coupled optimisation model of the European energy system (2024).

[24] Victoria, M., Zeyen, E. & Brown, T. Speed of technological transformations required in Europe to achieve different climate goals. *Joule* **6**, 1066–1086 (2022).

[25] Erntell, H., Dörner, K., Berger-de León, M., Flötotto, M. & Henz, T. European deep tech: What investors and corporations need to know (2024). URL `https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/european-deep-tech-what-investors-and-corporations-need-to-know`.

[26] Vinichenko, V., Jewell, J., Jacobsson, J. & Cherp, A. Historical diffusion of nuclear, wind and solar power in different national contexts: implications for climate mitigation pathways. *Environmental Research Letters* **18**, 094066 (2023).

[27] Neumann, F., Zeyen, E., Victoria, M. & Brown, T. The potential role of a hydrogen network in Europe. *Joule* **7**, 1793–1817 (2023).

[28] Energy Security Bill factsheet: Fusion regulation (2023). URL `https://www.gov.uk/government/publications/energy-security-bill-factsheets/energy-security-bill-factsheet-fusion-regulation`.

[29] U.S. Congress. Fusion Energy Act: H. R. 5244 (2023).

[30] Malhotra, A. & Schmidt, T. S. Accelerating Low-Carbon Innovation. *Joule* **4**, 2259–2267 (2020).

[31] Gruebler, A. The costs of the French nuclear scale-up: A case of negative learning by doing. *Energy Policy* **38**, 5174–5188 (2010).

[32] Berthélemy, M. & Escobar Rangel, L. Nuclear reactors' construction costs: The role of lead-time, standardization and technological progress. *Energy Policy* **82**, 118–130 (2015).

[33] Lovering, J. R., Yip, A. & Nordhaus, T. Historical construction costs of global nuclear power reactors. *Energy Policy* **91**, 371–382 (2016).

[34] Huenteler, J., Schmidt, T. S., Ossenbrink, J. & Hoffmann, V. H. Technology life-cycles in the energy sector — Technological characteristics and the role of deployment for innovation. *Technological Forecasting and Social Change* **104**, 102–121 (2016).

[35] Schyska, B. U., Kies, A., Schlott, M., von Bremen, L. & Medjroubi, W. The sensitivity of power system expansion models. *Joule* **5**, 2606–2624 (2021).

[36] Victoria, M., Zhu, K., Brown, T., Andresen, G. B. & Greiner, M. Early decarbonisation of the European energy system pays off. *Nature communications* **11**, 6223 (2020).

[37] Hörsch, J., Hofmann, F., Schlachtberger, D. & Brown, T. PyPSA-Eur: An open optimisation model of the European transmission system. *Energy Strategy Reviews* **22**, 207–215 (2018).

[38] Brown, T., Schlachtberger, D., Kies, A., Schramm, S. & Greiner, M. Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system. *Energy* **160**, 720–739 (2018).

[39] European Network Transmission System Operators of Electricity. Open Poewr System Data: Data Package Time Series (2018). URL `https://data.open-power-system-data.org/time_series/2018-03-13/`.

[40] Tchung-Ming, S., Mantzos, L., Wiesenthal, T., Matei, N. & Rozsai, M. *JRC-IDEES – Integrated Database of the European Energy Sector – Methodological note* (Publications Office, 2017).

[41] Ruiz, P. *ENSPRESO - BIOMASS: An open data, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials* (2019). URL `http://data.europa.eu/89h/74ed5a04-7d74-4807-9eab-b94774309d9f`.

[42] Victoria, M., Zhu, K., Zeyen, E. & Brown, T. PyPSA/technology-data: v0.9.2 (2024).

[43] Tran, B.-L., Chen, C.-C. & Tseng, W.-C. Causality between energy consumption and economic growth in the presence of GDP threshold effect: Evidence from OECD countries. *Energy* **251**, 123902 (2022).

[44] Freire-González, J., Padilla Rosa, E. & Raymond, J. L. World economies' progress in decoupling from CO2 emissions. *Scientific reports* **14**, 20480 (2024).

[45] Ferioli, F., Schoots, K. & van der Zwaan, B. Use and limitations of learning curves for energy technology policy: A component-learning hypothesis. *Energy Policy* **37**, 2525–2535 (2009).

[46] Danish Energy Agency. Technology Catalogues (2024). URL `https://ens.dk/en/analyses-and-statistics/technology-catalogues`.

[47] Bank, E. C. Policy and Exchange Rates: US dollar (USD) (2025). URL https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html.

[48] Griffiths, T., Pearson, R., Bluck, M. & Takeda, S. The commercialisation of fusion for the energy market: a review of socio-economic studies. *Progress in Energy* **4**, 042008 (2022).

[49] Cano-Megias, P. *et al.* Boosting the Efficiency of Future Fusion Power Plants Combining Energy and Heat Production. *IEEE Transactions on Plasma Science* **50**, 4430–4439 (2022).

[50] Global Energy Transition Tracker (2025). URL https://globalenergymonitor.org/.

[51] Where does Europe get its electricity? (2022). URL https://www.iea.org/regions/europe/electricity.

[52] Segantin, S., Testoni, R., Hartwig, Z., Whyte, D. & Zucchetti, M. Exploration of a Fast Pathway to Nuclear Fusion: Thermal Analysis and Cooling Design Considerations for the ARC Reactor. *Fusion Science and Technology* **76**, 45–52 (2020).

[53] *IEA Energy Technology RD&D Statistics* (2017).

[54] Brasington, L. Fusion Energy Innovation: Accelerated Progress in 2020 (2020). URL https://www.cleantech.com/fusion-energy-innovation-accelerated-progress-in-2020/.

[55] Palmer, M. Investors bet on fusion payoff within a decade (2023). URL https://globalventuring.com/corporate/energy-and-natural-resources/investors-nuclear-fusion/.

[56] Karunaratne, N. Dead Horse, Also-Ran, or Unicorn? How Nuclear Fits With Net Zero (2023). URL https://about.bnef.com/insights/clean-energy/dead-horse-also-ran-or-unicorn-how-nuclear-fits-with-net-zero/.

[57] Liebert, W., Bähr, R., Glaser, A., Hahn, L. & Pistner, C. Fortgeschrittene Nuklearsysteme: Review Study (1999). URL https://inis.iaea.org/collection/NCLCollectionStore/_Public/31/033/31033229.pdf.

[58] Bradshaw, A. M. Anhörung Kernfusion im Ausschuss für Bildung, Forschung und Technikfolgenabschätzung des Deutschen Bundestages am 28.3.2001 (2001). URL https://www.ipp.mpg.de/639630/bt_28_03_01.pdf.

[59] Grundwald, A., Gruenwald, R., Oertel, D. & Paschen, H. Thermonuclear Fusion - Current Status (2003). URL https://www.europarl.europa.eu/RegData/etudes/etudes/join/2003/323555/DG-4-JOIN_ET(2003)323555_EN.pdf.

[60] Energy Policies of IEA Countries: 2003 Review (2003). URL https://iea.blob.core.windows.net/assets/c59d4d2a-8165-48c9-9ff7-13c77a974a0b/EnergyPoliciesofIEACountries2003Review.pdf.

[61] Wurzel, S. Equity Investments to Fusion Energy Companies 2010-2023 by Country (2024). URL https://www.fusionenergybase.com/articles/equity-investments-to-fusion-energy-companies-2010-2023-by-country#fn:1.

[62] Wurzel, S. Fusion Energy Base Data Enquiry (12/06/2025).

[63] Fusion Industry Association. The global fusion industry in 2022 (2023). URL https://www.fusionindustryassociation.org/wp-content/uploads/2023/05/globalFusionEnergyReport.pdf.

[64] LLC, M. U.S. Inflation Rate (1960 - 2024) (2025). URL https://www.macrotrends.net/global-metrics/countries/usa/united-states/inflation-rate-cpi.

[65] Ben Bond-Lamberty *et al.* JGCRI/gcam-core: GCAM 7.1 (2024).

[66] National Renewable Energy Laboratory. Annual Technology Baseline (2015). URL https://atb.nrel.gov/archive.

A. Supplementary Information

A.1. Supplementary methods

As discussed in subsection 4.2, future technology costs are projected using learning curves for all technologies that do not reach saturation by 2050, defined as having less than 5% cost reduction between 2040 and 2050. Based on this threshold, the following 56 technologies are modeled with ongoing learning: Ammonia Cracker, BEV Bus City, BEV Coach, BEV Truck Solo Max 26 Tons, BtL, FCV Bus City, FCV Truck Solo Max 26 Tons, FCV Truck Trailer Max 56 Tons, Fischer-Tropsch, H2 Evaporation, H2 Liquefaction, Haber-Bosch, Hydrogen Fuel Cell (Passenger Cars), Liquid Fuels ICE (Trucks), Air Separation Unit, Battery Inverter, Battery Storage, Biogas, Biogas CC, Biogas Plus Hydrogen, Biogas Upgrading, Biomass CHP Capture, Biomass HOP, Biomass Boiler, Biomass-To-Methanol, Cement Capture, Central Ground-Sourced Heat Pump, Central Hydrogen CHP, Central Water Tank Storage, Decentral Air-Sourced Heat Pump, Decentral Gas Boiler, Decentral Gas Boiler Connection, Decentral Ground-Sourced Heat Pump, Digestible Biomass To Hydrogen, Direct Air Capture, Electrobiofuels, Electrolysis, Fuel Cell, Home Battery Inverter, Home Battery Storage, Hydrogen Storage Tank Type 1 Including Compressor, Hydrogen Storage Underground, Methanation, Methanol-To-Kerosene, Methanolisation, Micro CHP, Offwind-Float, Seawater Desalination, Solar, Solar-Rooftop, Solar-Rooftop Commercial, Solar-Rooftop Residential, Solar-Utility, Solar-Utility Single-Axis Tracking, Solid Biomass To Hydrogen, Waste CHP, Waste CHP CC.

Cost trajectories are manually specified by modifying PyPSA-Eur's resource files, bypassing the default cost retrieval function. Projections until 2050 are based on data from the Danish Energy Agency's Technology Catalogues and are extended through 2100. Details on cost assumptions, including fusion, and example trajectories are illustrated in Figure A.1.

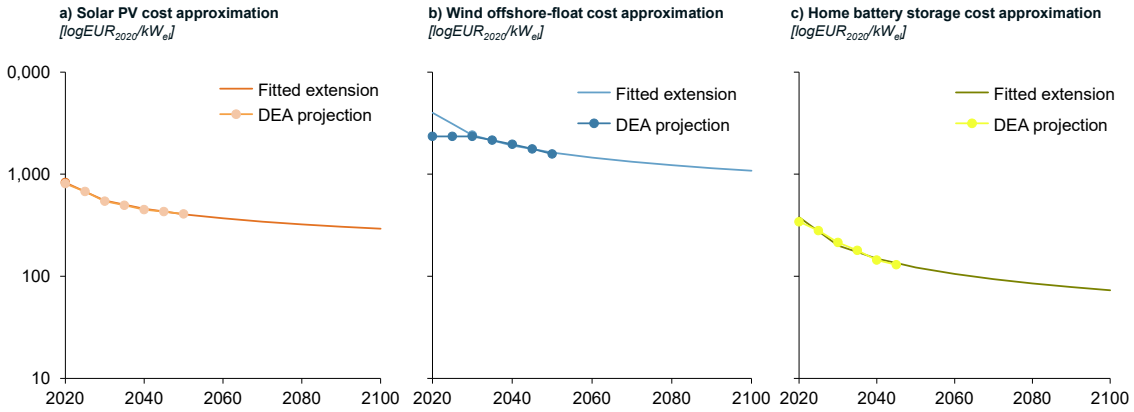

Figure A.1: *Illustrative cost curves derived by fitting cost projections in*[46] *with curves as provided in*[45]*. (Own illustration)*

Drawing on historical learning patterns from the nuclear fission industry, we adopt a conservative but continuous cost reduction trajectory for fusion. While early fission programs achieved learning rates of –5% to –15%, these gains were later offset by increasing complexity and regulatory hurdles. In contrast, South Korea maintained consistent cost declines. Anchoring our assumptions on this more optimistic precedent, we apply a modest –0.7% annual cost reduction for fusion, reflecting its potential regulatory advantages over fission. This continuous learning model offers a more differentiated alternative to the stepwise reductions typically used in prior studies. Cost reductions are assumed to begin upon fusion's market entry, as illustrated in Figure A.2.

A.2. Supplementary figures

From a systems perspective, renewables retain the largest share of installed capacity across all scenarios, consistently exceeding 50% of the future power system (see Figure A.3 in the supplementary information). By 2100, this capacity is roughly divided into two-thirds solar and one-third wind, with minimal deviation when fusion is introduced. The primary impact of fusion energy is its reduction of total installed capacity, with a decrease of -10 to -40% by 2050 and -20 to -70% by 2100. The share of solar power increases throughout the century compared to wind due to higher learning rates assumed by PyPSA-Eur[23], as applied in this study.

Similar patterns emerge in the generation mix. Under constraints, renewables remain dominant. Without constraints, however, fusion provides 67% of electricity by 2100, while renewables, despite making up 59% of installed capacity, contribute just 29% due to lower capacity factors. Fusion,

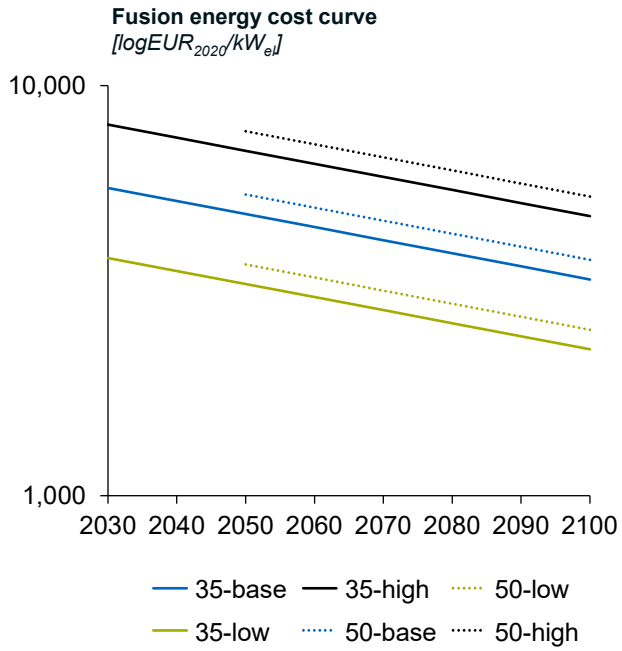

Figure A.2: *Fusion cost progression assuming a learning rate of 0.7% based on the South Korean experience in nuclear fission[33]. (Own illustration)*

as a baseload source, outperforms solar and wind, which require 5–6x and 2–3x more capacity, respectively, to deliver equivalent output. As a result, solar and wind contribute nearly equally to generation despite solar's higher capacity. Fission, although present in installed capacity by 2050, contributes no generation due to prohibitive costs of approximately 8,000 EU/kW_{el}[24].

When comparing our findings to the existing academic discourse (see Figure A.4), we find that our results are relatively conservative, generally aligning with the lower bound of the trend lines indicated by previous studies. This is likely attributable to the broader global potential of fusion energy, which exceeds what is achievable within the European context alone. Analyzing fusion's deployment across the three identified phases, we observe that the technology benefits significantly from periods of high demand growth - a trend also observed in the historical diffusion of nuclear fission during the 1970s[26]. Expanding the analysis to include regions with strong future demand growth, particularly in developing countries, where the coupling between economic development and energy consumption remains robust[43,44], would naturally increase fusion's global market potential. Our modeling of fusion energy relies on conservative assumptions regarding both costs and operational characteristics. The cost estimates are based on mean values from the literature, and the learning rate is derived from the experience of nuclear fission deployment in South Korea[33]. One could argue that this learning rate may underestimate future cost reductions in fusion, as much of the cost escalation in fission has been linked to regulatory complexity and mid-construction design changes[31–33]. Given the potentially simpler and inherently safer design of fusion reactors, more optimistic learning trajectories could be plausible. On the operational side, fusion plants are assumed to exhibit baseload characteristics similar to those of fission power plants. This is in line with[3],

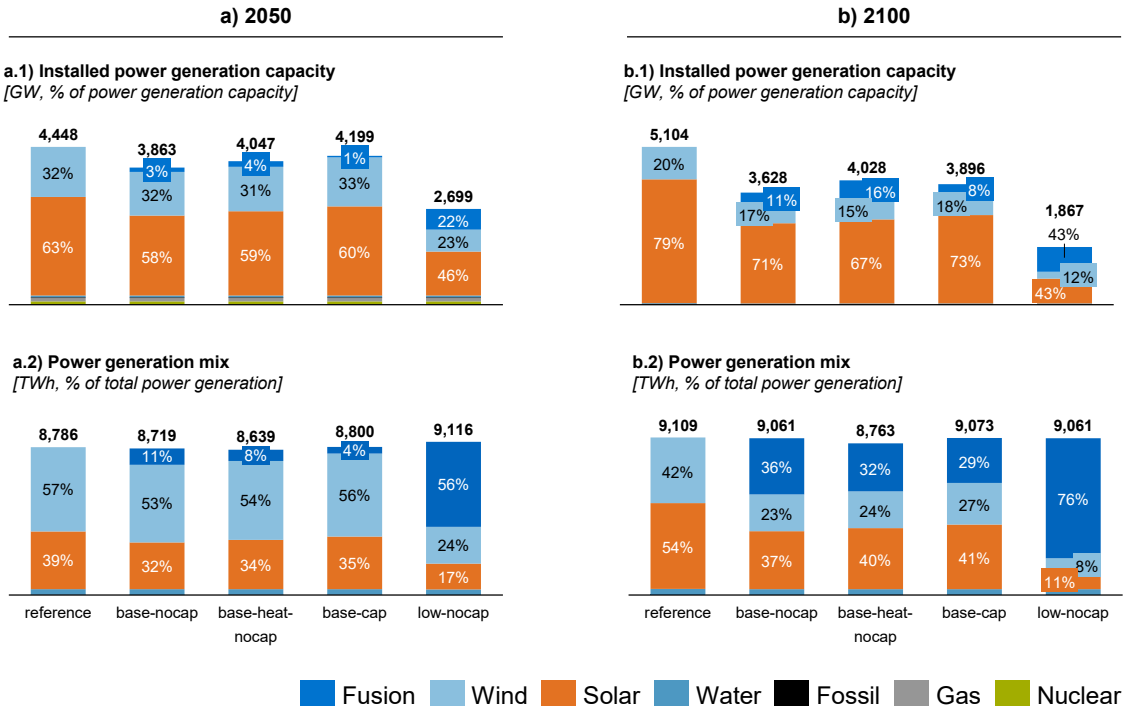

Figure A.3: *Installed system capacity and generation mix for 2050 and 2100 in fusion35 main scenarios. Note: Only shares >5% displayed except for fusion energy. (Own illustration)*

where the authors find that pulsed operation and other constraints are unlikely to significantly limit fusion's role.

Additionally, the cost assumptions in PyPSA-Eur may be way more favorable for renewables and, hence, competitive against fusion, than the assumptions used in other studies. While the assumptions are not explicitly stated, the underlying Global Change Assessment Model in [14] uses the Annual Technology Baseline (TAB) by the U.S. National Renewable Energy Laboratory[65]. By 2050, the TAB projects capital costs for utility-scale solar PV that are almost 5 times higher than those in the Danish Energy Agency (DEA) Technology Catalogue used in PyPSA-Eur. PyPSA-Eur assumes a 40-year lifetime by 2050, whereas the TAB uses a 20-year economic lifetime[46,66]. With a 0.3% annual degradation, the Technology Catalogue still ensures 88% higher availability compared to the TAB's shorter lifetime. This discrepancy likely explains why fusion competitors are not cost-effective compared to renewables in PyPSA-Eur. Despite including diverse technologies like fission, CCS, and hydrogen turbines, these are not economically competitive and are not adopted even in the reference case without fusion. Therefore, PyPSA-Eur's optimistic cost assumptions for renewables, combined with our conservative fusion modeling, likely bias the results toward underestimating fusion's potential contribution. Our findings should be seen as a lower-bound estimate of fusion's competitiveness in future energy systems.

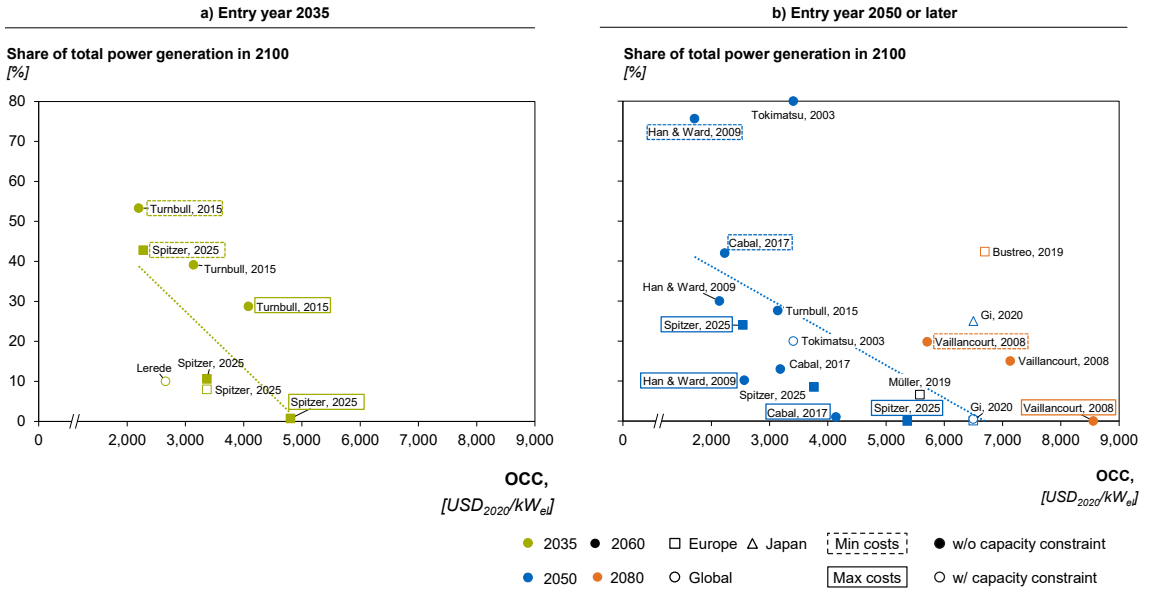

Figure A.4: *Mapping of energy generation market shares by 2100 over OCCs including core modeling assumptions (fusion entry year, geographic scope, cost level, and capacity constraint) in the present work ("Spitzer, 2025") and relevant studies[3,12–19,22]. Note: References abbreviated for better legibility. OCCs are given with end-of-modeling-period values if cost degression is assumed[13,14,18]. (Own illustration)*

Contact.

MIT CEEPR Working Paper Series
is published by the MIT Center for Energy and Environmental Policy Research from submissions by affiliated researchers.
For inquiries and/or for permission to reproduce material in this working paper, please contact:

General inquiries: ceepr@mit.edu
Media inquiries: ceepr-media@mit.edu

MIT CEEPR

Center for Energy and
Environmental Policy Research

MIT Center for Energy and
Environmental Policy Research
Massachusetts Institute of Technology
77 Massachusetts Avenue, E19-411
Cambridge, MA 02139-4307
USA

ceepr.mit.edu

MASSACHUSETTS INSTITUTE OF TECHNOLOGY