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Perspective

Baseload power plants are not essential for future power systems

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SUMMARY

The transition to decarbonized energy systems has fueled a controversial debate over the necessity of traditional “baseload” power. Skepticism remains regarding the reliability and economic feasibility of power systems relying mainly on cheap variable renewable energy (VRE) sources. Addressing this, the German Academies’ project “Energy Systems of the Future” (ESYS) analyzed the role of baseload power plants within a decarbonized, continental-scale energy system. Their findings indicate that a secure, net-zero European electricity system is technically robust and economically viable when based on VRE paired with extensive flexibility, storage, and grid interconnections, without requiring new baseload capacity. The integration of new low-carbon baseload technologies, such as nuclear fission or fusion, natural gas with carbon capture and storage (CCS), or geothermal energy, has a marginal impact on overall system costs. While low-cost baseload technologies could be efficiently integrated to achieve high utilization, their future role is contingent on achieving cost reductions beyond current realities.

INTRODUCTION

The rapid cost decline and deployment of variable renewable energy (VRE) sources, particularly solar photovoltaics (PV) and wind, have shifted them from niche contributors to the central pillars of decarbonization strategies. A growing body of research using cost-optimization models suggests that a system dominated by VRE, complemented by demand-side flexibility, grid interconnections, and a portfolio of storage technologies such as batteries and hydrogen, is the least-cost pathway to a fully decarbonized energy system.[1–5] Some suggest energy systems that fully rely on the renewable electricity sources wind, solar, and hydropower,[3] while other scenarios of 100% renewables also include biomass or synthetic gas as dispatchable power sources.[5] Notwithstanding, a persistent and polarized debate continues over the role of continuously operating low-carbon power plants, often referred to by the legacy term “baseload.” Proponents argue that technologies such as nuclear, geothermal, or natural gas with carbon capture and storage (CCS) are important to ensure grid reliability and contain overall system costs.[6–8] They argue that nuclear[6] or a combination of nuclear, gas with CCS, and bioenergy[7,8] leads to the lowest cost of achieving

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high levels of decarbonization. However, these studies often do not fully account for the electrification of industry, transport, and heating but either assume current electricity needs[6,7] or only modest changes to today's demand profiles,[8] thereby underestimating future demand flexibility.

This debate raises the following questions: are baseload power plants necessary in low-carbon energy systems? Can they achieve the high utilization that would actually classify them as baseload plants, and is this option economically reasonable? The answers are not only interesting for academia; they have profound implications for infrastructure investments and national energy strategies. To provide a data-driven foundation for this discussion, the German Academies' project "Energy Systems of the Future" (ESYS) conducted a comprehensive analysis based on detailed, hour-by-hour system modeling for a decarbonized Europe.[9,10] The study evaluates the systemic value and economic viability of new low-carbon baseload technologies within a fully decarbonized European energy system by 2045. The findings reveal that, while these technologies are integrable, they are not a prerequisite for a secure and low-cost energy supply. Moreover, their potential contribution is constrained by generation costs that appear infeasible without massive cost breakthroughs.

From baseload to flexible firm capacity

The term "baseload power plant" originates from an energy paradigm where large thermal stations with low operating costs run continuously to meet minimum continuous electricity demand over the year. The resulting high utilization of these plants justifies the large capital investment, leading to designs optimized for steady output rather than rapid ramping. Within this framework, system flexibility from storage or demand-side management is valued for its ability to smooth the load profile, thereby increasing the utilization of these capital-intensive baseload assets. While moderate capacities of VRE can act as a "fuel saver," building too much creates inefficient capacity redundancy, as the system is already optimized around firm generation.

Today's cost structure, with VRE now being the cheapest form of energy in many locations of the world, forces a corresponding paradigm shift in system operation. In a VRE-dominated grid, the central challenge shifts from meeting a load that follows predictable patterns of base and peak load to managing the fluctuating residual load (demand minus VRE generation). Consequently, the primary value of flexibility shifts from accommodating inflexible thermal plants to integrating variable generation. As high-VRE systems inherently require significant flexibility resources (e.g., storage, responsive demand) to cope with this variability, a new set of questions arises: can baseload technologies still provide systemic value? And can they reach the high utilization needed to justify their capital-intensive cost structure? These questions cannot be answered by comparing component costs alone but require integrated system modeling at high temporal and spatial resolution to determine the truly cost-optimal technology mix.

Economic challenges and a reality check on contenders

To quantify the economic viability threshold for baseload power, we modeled the cost-optimal expansion of the European energy system to 2045, making a generic baseload technology available under varying cost assumptions. To reflect current policies promoting renewable energies, we assumed a minimum VRE expansion pathway (e.g., half of Germany's Renewable Energy Act targets).

This approach identifies the cost boundaries at which new baseload capacity becomes competitive (Figure 1). The results demonstrate that new baseload capacity is only integrated if it is sufficiently cheap, and, when built, the system optimizes its operation to achieve high utilization. For capital expenditures (CAPEX) of 15,000 €/kW and beyond, no new capacity is built. CAPEX is defined as all costs related to the construction of a plant until start of operation, including interest during construction. Likewise, a CAPEX of 10,000 €/kW proves uncompetitive when paired with relatively high variable operating costs. The highest levelized cost of electricity (LCOE) at which any baseload capacity enters the optimal system mix is approximately 80 €/MWh. The LCOE is determined *ex post* using the utilization realized in the model dispatch (measured in full-load hours). This indicator has proved to be the best proxy for the share of baseload power plants across the various implemented parameter sets. A substantial baseload expansion capable of displacing VRE investment only happens under the assumption of very low—in today's perspective, likely unrealistic—cost assumptions for the baseload technologies (LCOE of 40 €/MWh or less); in all other cases, VRE remained the dominant source for new generation. These results assumed a social discount rate of 2%, representing a macroeconomic rather than an investor perspective. The results are consistent with similar studies with a European scope.[11,12]

This cost threshold provides a crucial reality check when assessing the primary contenders for a future low-carbon baseload role: nuclear fission, natural gas with CCS (Gas-CCS), geothermal, and nuclear fusion.

While technically mature, new nuclear fission power plant construction in Western economies is plagued by profound techno-economic challenges.[13] Recent projects (e.g., Olkiluoto 3 in Finland, Flamanville 3 in France, Hinkley Point C in the UK, or Vogtle 3 and 4 in the US) have experienced multi-year delays and cost overruns that have pushed final CAPEX into the 10,000–15,000 €/kW range or higher, placing them close to or beyond the viability threshold identified in our analysis. In France, EDF is currently struggling to keep cost projections for new projects under control. The promise of small modular reactors (SMRs) improving this economic outlook remains largely theoretical, with no commercial prototypes yet deployed, and the leading US project recently canceled due to soaring cost estimates.

Gas-CCS is often presented as a more near-term dispatchable option. However, it faces its own set of significant hurdles. The energy penalty of current capture technologies reduces net plant efficiency, and achieving net-zero compatibility requires accounting for incomplete CO_2 capture and potentially significant upstream methane emissions. Crucially, building the required CO_2 transport and storage infrastructure requires massive investment beyond the plant's CAPEX. From an operational perspective, variable operating costs highly depend on volatile natural gas prices, further challenging its competitiveness.

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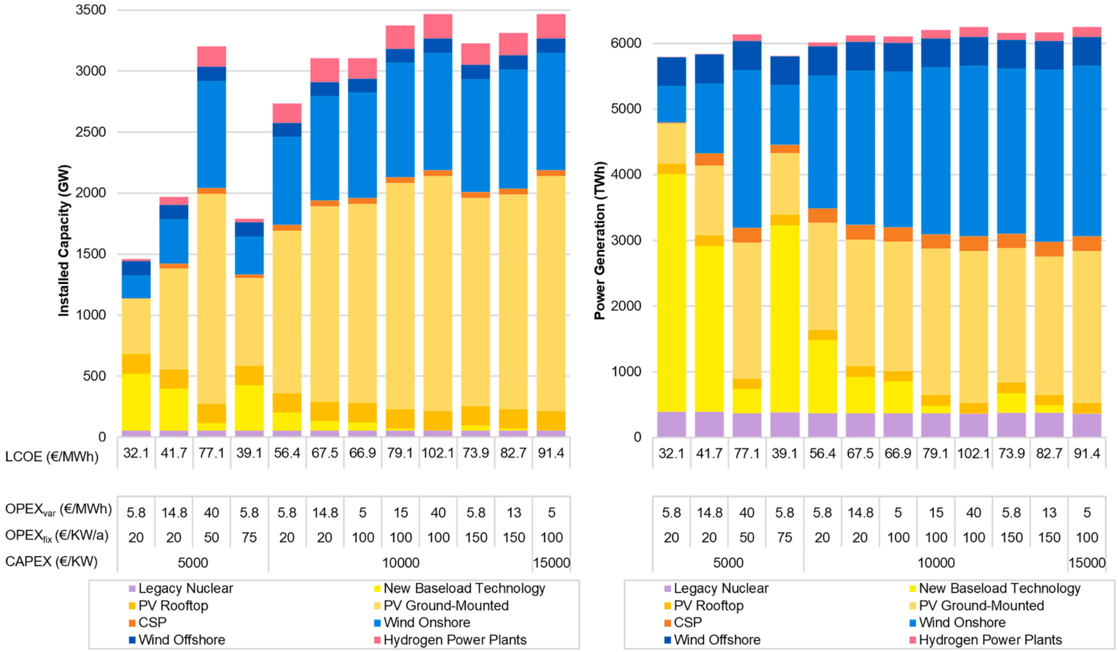

Figure 1. Installed capacity and electricity generation for 2045 in Europe under varying cost assumptions for a baseload power plant technology

Cost assumptions for the other technologies are based on the long-term scenario 3 for the German Federal Ministry for Economic Affairs and Energy (2020). These are (OPEX$_{var}$ | OPEX$_{fixed}$ | CAPEX): Solar PV rooftop 0 €/MWh | 11.6 €/kW/a | 774 €/kW; solar PV utility-scale 0 €/MWh | 8.9 €/kW/a | 356 €/kW; wind onshore 0 €/MWh | 14.6–20.2 €/kW/a | 984–1,367 €/kW; wind offshore 0 €/MWh | 54.3–59.6 €/kW/a | 2,511–2,873 €/kW.

Geothermal electricity generation is geographically constrained, and, while enhanced geothermal systems could expand its potential, they are not yet commercially mature.

Nuclear fusion remains a distant, long-term prospect, highly unlikely to significantly contribute to the energy supply before the second half of the 21st century.

Dispatch patterns with and without baseload capacity

Setting aside the conclusion that cost targets for the considered baseload technologies appear unlikely to be achieved, we investigated their system integration in a hypothetical case of substantial expansion. We fixed the addition of new baseload capacity at 60 GW in Europe by 2045 (20 GW for Germany), an amount considered the upper limit of what is realistically achievable. The cost assumptions used in the model resemble those of nuclear power and Gas-CCS plants, respectively (see methods for specific assumptions). The newly built capacity adds to existing nuclear power plants and replacements, summing up to an overall capacity of 115 GW in 2045, most of which would need to be newly built by this date. It would require an average of 10 GW of additions per year from 2035 onward, matching Europe's peak nuclear construction rate of the 1980s. This is a pace that even current nuclear-promoting alliances consider challenging, underscoring the significant industrial effort required for such a build-out.

A comparison of the cases with and without the baseload option shows that the general generation patterns do not differ significantly (Figures 2 and 3). Both cases are characterized by a massive expansion of solar PV and wind, supported by a significant build-out of flexible-demand technologies along with interconnections and storage. The baseload capacity is small in comparison, thereby not changing the system operation much.

The economic viability of baseload power plants turns out to be connected with a large-scale hydrogen economy. Conversely, the flexibility option that is most sensitive to the availability of baseload generation is hydrogen production. In the model, 40% of the generation from new German baseload capacity is used for water electrolysis, which in turn enables the baseload plants to operate at the high capacity factors (>6,500 h/a) that ensure their economic viability. Electrolysis is thus a pivotal flexibility provider for integrating both VRE and baseload generation. Uncertainty surrounding the large-scale deployment of hydrogen electrolysis therefore also impacts the economic case for baseload power plants. The future cost of electrolyzer systems and their capacity factor are among the most critical factors affecting the timing of the transition to electricity-based hydrogen.[14]

The addition of new baseload capacity has only a marginal impact on total system costs. In scenarios where an ambitious 60 GW of new baseload capacity with a CAPEX of 10,000 €/kW and variable operating costs of 15 €/MWh (very optimistic numbers for nuclear power plants) is added to the European system by 2045, undiscounted optimal system costs were about 0.5% higher than in the reference system without the fixed baseload additions. For Gas-CCS, the comparison is more difficult as such systems require additional investments into gas and CO_2 infrastructures that are beyond the model scope. The cost differences fall well within the range of uncertainty for future

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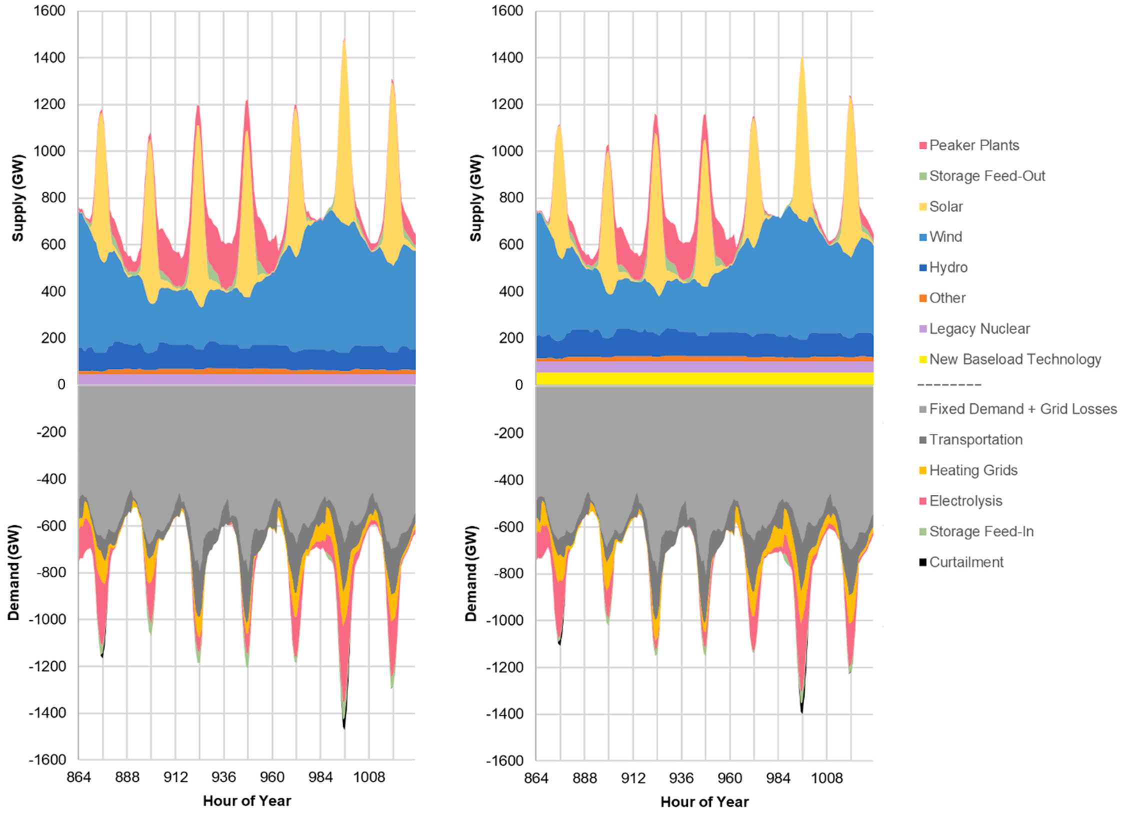

Figure 2. Hourly dispatch in the European power system during the winter

Hourly dispatch is shown during a low-wind winter week (February), without additional baseload plants (left) and with (right).

technology costs,[15,16] suggesting there is no strong case for baseload power plants.

Outlook

The debate about baseload power needs to evolve. System-level modeling for Europe shows that the question is not whether new baseload plants are essential for a secure, net-zero grid—they are not. The defining question is whether they can become economical in a system dominated by low-cost renewables. The evidence suggests their competitiveness is questionable, requiring costs that current projects consistently fail to achieve.

Given the lack of a compelling system-wide economic benefit, committing to large-scale long-lived, and capital-intensive baseload projects carries significant financial risk. It can create important path dependencies that reduce the flexibility to adapt to future technological developments. It should be noted, however, that our study evaluates system design and dispatch for a single weather year and only for the European power system. The selected year featured below-average output from variable renewables, representing a conservative assumption with respect to VRE deployment. Previous analyses examining the effects of varying weather conditions in the European context indicate that interannual weather variability can influence optimal system configurations, leading to variations of approximately ±10% in total system costs. However, these variations do not alter the fundamental conclusion that high shares of wind and solar remain cost-competitive.[17] Nevertheless, testing additional and particularly extreme weather years would be valuable to ensure that no potential advantages of baseload power plants are overlooked.

While the economics for baseload power plants might differ between world regions and also depend on the cost developments of VRE and flexibility technologies, most pathways to a reliable, affordable, and decarbonized energy future involve the rapid and massive expansion of renewable energy, underpinned by a robust and flexible grid, diverse short- and long-duration storage options, and demand-side flexibility. Policy and investment should therefore focus on accelerating the deployment of these proven, scalable, and increasingly cost-effective technologies to meet near-term climate targets. Particularly, developing flexibility is a necessity in all cases and can be seen as a no-regret measure. Key measures to enhance system flexibility include advancing market designs that provide effective incentives for optimal flexibility deployment as well as promoting stronger electrification and digitalization.

While the door for new baseload technologies should not be permanently closed, they must earn their place by overcoming their considerable economic barriers. Until then, they remain a costly and uncertain detour from the main road of the energy transition.

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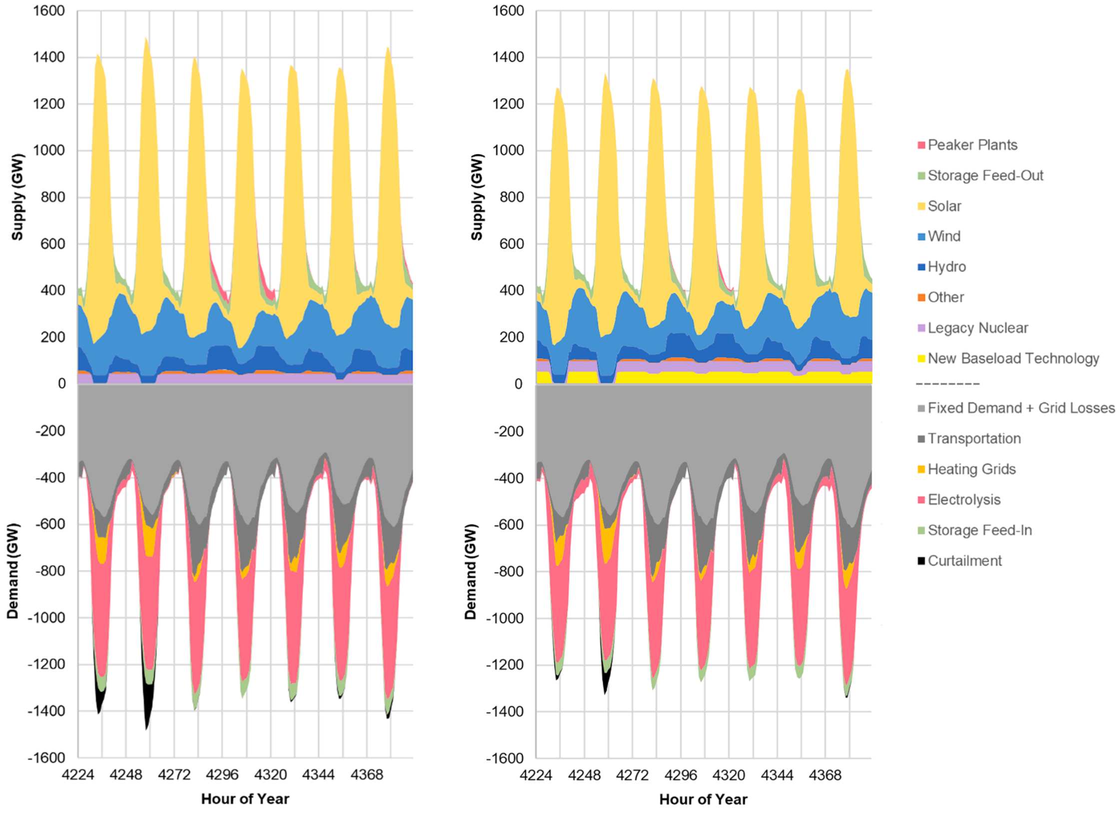

Figure 3. Hourly dispatch in the European power system during the summer

Hourly dispatch is shown in a sunny summer week (June), without additional baseload plants (left) and with (right).

METHODS

The data within the perspective is obtained from the discussion paper "Nuclear Fission, Natural Gas, Geothermal Energy, Nuclear Fusion. The Future Role of Baseload Power Plants," which can be accessed via https://en.acatech.de/publication/baseload-power-plants/. The full documentation of the model runs is also provided under https://energiesysteme-zukunft.de/fileadmin/user_upload/Publikationen/PDFs/ESYS_ISI_Gutachten_Grundlast.pdf (in German). The cost assumptions referred to in the perspective are as follows: OPEX$_{\text{var}}$ 15 €/MWh, OPEX$_{\text{fixed}}$ 100 €/kW/a, CAPEX 10,000 €/kW for nuclear and OPEX$_{\text{var}}$ 53 €/MWh, OPEX$_{\text{fixed}}$ 20 €/kW/a, and CAPEX 1,250 €/kW for Gas-CCS.

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AUTHOR CONTRIBUTIONS

Conceptualization, investigation, and validation: all authors. Writing – original draft: A.W. Writing – review & editing: A.W., P.S., K.P., W.-P.S., and C.L. Formal analysis, data curation, software, and visualization: C.L. and F.S. Methodology and supervision: K.P., M.F., H.-M.H. and D.U.S. Project administration: P.S., B.E., C.S., and S.W.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the authors used Gemini 2.5 Pro to improve the language and readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article. AI tools were not used for any technical analysis.

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