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Energiewende perspectives

GERMANY AT A CROSSROADS

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EXECUTIVE SUMMARY

Germany's energy sector is at a pivotal moment, facing significant challenges in ensuring a reliable and affordable energy supply while also meeting its climate goals. The recent Monitoring Report¹ from the Federal Ministry for Economic Affairs and Energy highlights the need for a more pragmatic approach to energy policy, one that acknowledges the complexities of the energy system and the need for a more nuanced approach. There is a need for a more useful framework for addressing the challenges of the German energy industry, emphasizing the importance of honest demand assessment, market-oriented renewables, and a technology-open capacity market.

In this white paper, GE Vernova offers commentary on the Monitoring Report and a distinct perspective on the German energy landscape, one that leverages our internal expertise and data analysis to provide a comprehensive and accurate picture of the market. Firstly, we establish a model for the expected trajectory of German energy demand, supply, and the consequences for pertinent parameters like curtailment and expected energy not served (EENS). We also model additional hypothetical scenarios entailing a recession and supply chain shock to illustrate how Integrated Systems planning can help Germany prepare for uncertainty and constraints outside the trilemma framework. We subsequently offer reflections on the government's 10-Point-Plan, including considerations of how to expand and adapt them to the Integrated Systems approach. This complements the Monitoring Report's approach, which provides a broad overview of the uncertainty space, and together they offer a powerful toolkit for understanding and navigating the complexities of the German energy landscape.

To address the energy system challenges in Germany, a comprehensive and integrated approach to energy planning is necessary. This involves considering the entire energy system, including power generation, demand, grid infrastructure, and supply chains. By taking a more holistic view, Germany can identify opportunities to improve efficiency, reduce costs, and enhance the resilience of its energy system.

A key aspect of this approach is the development of a flexible and adaptable energy market. This can be achieved through the implementation of capacity and capability markets that encourage investment in new energy technologies and provide a stable revenue stream for energy providers. Additionally, Germany must prioritize the development of digital technologies, such as smart grids and energy storage systems, to manage the variability of renewable energy sources and ensure a stable energy supply.

However, Germany's energy security is also vulnerable to risks associated with its supply chains and cybersecurity. To mitigate these risks, the country should diversify its energy imports and invest in domestic energy production. Strategic investments in technology innovation and digitization for the grid will also be critical.

The next few years will be critical in determining the future of Germany's energy sector. By adopting a more integrated and holistic approach to energy planning, the country can unlock new opportunities for growth and development, while also ensuring a reliable and affordable energy supply for its citizens. This will require careful planning, coordination, and investment, but the potential rewards are significant, and the consequences of inaction could be severe.

¹<https://www.bundeswirtschaftsministerium.de/Redaktion/DE/Publikationen/Energie/energiewende-effizient-machen.html>



INTRODUCTION

In September 2025, the Federal Ministry for Economic Affairs and Energy (BMWE) released its Energy Transition Monitoring Report. The meta study outlined an evaluation of German economic policy and consideration of where it ought to be altered, as well as where it should stay the course. Overall, the Monitoring Report (*“Energiewende. Effizient. Machen.”*) and accompanying 10-point paper (*“Klimaneutral werden – wettbewerbsfähig bleiben”*) were together a clarion call for energy pragmatism.

Both reports suggest that the current state of Germany’s Energiewende is technically feasible but economically vulnerable, and the reports put system efficiency at the center of things. To continue the energy transition in line with expanded deployment of renewables requires security of supply and enhanced flexibility. This further requires a focus on cost efficiency and economic competitiveness. The Monitoring Report ultimately argues that the current policy path risks becoming unrealistic, with demand, hydrogen, and grid build-out assumptions diverging from reality. The costs of the system need deeper analysis so that policymakers and the public can more transparently see the trade-offs, cost drivers, and efficiency impacts of different policy choices. The Monitoring Report recommends six core themes for ongoing monitoring in particular: energy demand, renewables expansion, build out of the transmission and distribution grid, hydrogen ramp-up, supply security, and digitalization using smart meters. To achieve a more optimal energy policy, the 10-point paper calls for realistic planning, market-oriented renewables, a capacity market, more grid flexibility and digitalization, fewer subsidies, and realism in hydrogen and CCS rollout.

The Monitoring Report highlights a need to rethink how the energy industry will evolve in Germany. Energy policy is typically understood in the context of the energy trilemma, the complex challenge of balancing three fundamental objectives: energy security, energy affordability, and environmental sustainability. Energy security focuses on ensuring a reliable and uninterrupted supply of energy to meet societal and economic needs. Energy affordability emphasizes the economic accessibility of energy for all segments of the population, aiming to prevent energy poverty and promote

social inclusion. Environmental sustainability addresses the imperative to minimize the ecological impact of energy production and consumption, including greenhouse gas emission reductions and promotion of renewable resources.

However, the Monitoring Report illustrates the insufficiency of this framework, which does not account for the many nuances and hard constraints of the energy system. Germany faces rising risks of expected energy not served (EENS) and growing renewables curtailment by the 2040s if flexibility, grid infrastructure, and secure capacity do not keep pace. Beyond the pillars of the energy trilemma alone, policy makers and system operators must analyze factors like market design, geopolitical realities, climate change, competitiveness, system cost efficiencies, and potentially other parameters as they arise over time.



We propose the practice of Integrated Systems Planning as the mechanism to evaluate these multidimensional nuances and constraints. Integrated Systems Planning provides a comprehensive approach to energy system development that considers the coordinated planning and optimization of multiple components and sectors within the energy system. The Monitoring Report and the government's 10-point plan underline how today's energy-only market design is insufficient. New market mechanisms—such as a capacity framework by 2027, as well as other possible reforms like a capabilities market—and updated regulatory openness will be essential to safeguard supply, enable competition, and reduce overall system costs. Additionally, new advanced generation technologies are needed to maintain stability and reliability, meet present and future decarbonization targets, and adapt to large loads. These technologies must also meet evolving regulatory requirements and their full benefits be

incentivized through ancillary services market mechanisms to most effectively deploy system-wide integrated solutions. Integrated Systems Planning responds to the Monitoring Report's approach by considering the whole system: generation, demand, grids, flexibility, markets, and supply chains. Utilizing this approach can unlock efficiency gains that lower the cost of the transition while strengthening resilience. Ultimately, energy planning must deliver affordable prices for consumers, reliable supply for businesses, and sustained economic growth in uncertain times.

The energy industry is undergoing one of its most dynamic moments, arguably in its history. Germany's choices, given its economic weight and geopolitical exposure, will materially influence Europe's pathway.



THE CONTEXT OF GERMAN ENERGY POLICY

It is worth reflecting on the history of Germany's energy policy in assessing its experience in managing a comprehensive framework for the energy transition through its own national leadership and European Union directives.

Domestic Energy Policy

From 1982 to 1998, government policy was characterized by a focus on nuclear energy and developing the internal energy market. This period coincided with the reunification of Germany, necessitating the integration of East Germany's coal-heavy energy system into the national framework, a process facilitated by EU frameworks like the European Coal and Steel Community (ECSC) and the European Atomic Energy Community (Euratom). These frameworks sought to integrate coal, steel, and nuclear industries post-war, laying the groundwork for future policy adaptations. Between 1998 to 2005, Germany initiated a shift towards renewable energy, introducing the Renewable Energy Act (EEG) in 2000. This act provided guaranteed feed-in tariffs for renewable producers, encouraging investment and marking Germany's first nuclear phase-out. The *Stromeinspeisungsgesetz*, or Feed-In Law, allowed renewable producers to feed electricity into the grid at fixed prices, fostering investment.

Following the Fukushima disaster in 2011, Germany reinstated the *Atomkonsens*, aiming for complete nuclear exit by 2022, and transitioned EEG to auction pricing in 2017 to address market dynamics. While the renewable sector thrived, the *Atomkonsens* entailed trade-offs, resulting in a small increase in fossil use and wholesale price impacts of about several Euros per MWh.² Nevertheless, Germany is currently projected to achieve ~60–65% reduction by 2030 vs 1990, subject to sectoral risks.³

The most recent Germany energy policy framework focused on exiting coal by 2030, expanding hydrogen infrastructure, and enhancing resilience, particularly in response to the Ukraine crisis. The *Kohleausstiegsgesetz*, or Coal Exit Law, targeted a reduction of coal-fired capacity to 8GW for hard coal and 9GW for lignite by 2030, accelerating the phase-out timeline. The *Klimaschutzgesetz*, or Climate Protection Act, sets binding CO₂ reduction targets for Germany, aiming for a 65% decrease by 2030 and climate neutrality by 2045.

At the onset of Russia's invasion of Ukraine, the government passed the LNG Acceleration Law. The law accelerated permitting for Floating Storage and Regasification Units (FSRUs) and onshore terminals to diversify away from Russian gas, trading speed for temporary environmental flexibilities.

EU policy frameworks

The interplay between national objectives and EU directives continues to shape Germany's energy landscape, requiring ongoing adjustments to meet evolving needs to balance climate targets and economic realities. EU regulation requires increased grid flexibility, causes decentralized energy generation, and establishes grid interdependencies. Regulation (EU) 2019/943, passed in June 2019, sought to create a harmonized and integrated electricity market within the EU, fostering competition, sustainability, and security through systematic and market-based approaches. The Fit for 55 policy, which sets a target of 55% GHG reductions by 2030 across Europe, in addition to regional climate and energy policies, has resulted in a continent-wide shift and rapid deployment of inverter-based and distributed energy resources.

² <https://www.sciencedirect.com/science/article/pii/S0301421524002283>

³ <https://ember-energy.org/countries-and-regions/germany/#:~:text=Highlights,Zero%20Emissions%20scenario%20of%2060%25.>

Regulation (EU) 2024/1747 updates elements of the electricity market design, including rules for capacity mechanisms (technology-neutral, proportionate, with cross-border participation) and stronger transparency/data-exchange obligations. It expands the Agency for the Cooperation of Energy Regulators' (ACER) role in approving ENTSO-E/EU DSO-Entity proposals on flexibility data and methodologies. It maintains the single allocation platform under 2016/1719 and refines cross-border allocation processes.

Further amendments are made to Regulation (EU) 2016/1719, which originally set the foundation for establishing a single capacity allocation platform across borders. The updates aim to ensure that this platform continues to operate smoothly, enhancing market operations and facilitating cross-border electricity trade, and seek to maintain an efficient and interconnected energy market across the EU.

A major consequence of Regulation (EU) 2024/1747 will be greater integration at the TSO-DSO interface through longer-term planning. As prosumers and microgrids expand their footprint across the grid, the regulatory impetus to ensure flexibility will require improved mechanisms for coordination, communication, and reliability, in addition to the flexibility mandate. This necessitates deeper systems thinking and deployment of advanced technological capabilities.

Regulation (EU) 2024/1747 builds upon existing EU legislation, such as Regulation (EU) 2019/943, which defines the Reliability Standard and European Resource Adequacy Assessment (ERAA) methodology. This methodology serves as the basis for Germany's resource adequacy monitoring, and the Bundesnetzagentur (BNetzA) uses it to conduct adequacy assessments. The System Operation Guideline (SO GL), Regulation (EU) 2017/1485, also plays a crucial role in shaping German policy, as it mandates TSO-TSO coordination and methods for cross-border redispatch. This has led to the development of Germany's Redispatch 2.0 framework, which includes DSOs in redispatch coordination with TSOs. As a result, German law, specifically the Energy Industry Act (EnWG), has been transposed to incorporate EU requirements, ensuring that the country's energy market design aligns with EU regulations.

In the context of the German power grid, the implementation of EU regulations has led to the development of various policy levers aimed at activating flexibility measures to balance the grid. For instance, §14a controls enable the activation of flexibility measures, such as load management, generation management, and storage activation, to ensure grid stability. Additionally, variable tariffs, aggregator access, and direct marketing are used to incentivize consumers to adjust their energy consumption in response to price signals, providing additional flexibility to the grid. These policy levers are designed to promote the integration of renewable energy sources, reduce peak demand, and alleviate grid congestion.



THE MONITORING REPORT - OVERVIEW AND COMMENTARY

Amidst this backdrop of Germany's policy context, the Monitoring Report landed from the German government as a reset of sorts to maintain the Energiewende's momentum while asserting an updated view of Germany's best interest. The government wanted to establish a checkpoint evaluation of what the realities are on the ground in the energy sector and to declare what is working, what is not, and what to do about any gap.

In its memo "*Klimaneutral werden - wettbewerbsfähig bleiben*" the government laid out 10 recommendations for energy policy:

- i. Honest demand assessment and planning realism
- ii. Promote renewable in a market- and system-oriented way
- iii. Expand grids, renewables, and decentralized flexibility in sync
- iv. Quickly implement a technology-open capacity market
- v. Advance flexibility and digitalization of the power system
- vi. Preserve and expand unified and liquid energy markets
- vii. Review support schemes, systematically reduce subsidies
- viii. Promote forward-looking research and innovation
- ix. Promote hydrogen ramp-up pragmatically, reduce overcomplex rules
- x. Establish CCUS as a climate protection technology

As aforementioned, these recommendations come on the back of the document "*Energiewende. Effizient. Machen.*", which notes six themes (generation, demand, grids, flexibility, markets, and supply chains) deemed necessary for ongoing monitoring to maintain a transparent view and realistic response to the actual state of the energy sector. To this end, the Monitoring Report conducts a comparative study that provides an overview of the uncertainty space surrounding the country's energy landscape, synthesizing a range of external studies from sources such as Agora Energiewende, ESYS,

Ariadne, McKinsey, BDI/BCG, and E-Venture. This approach involves a review of existing studies and data, resulting in a wide range of possible demand scenarios that reflect the complexities and uncertainties of the energy landscape. The report's demand assessments incorporate electrolysis demand, with a projected electrolysis demand of up to ~75 TWh by 2030, and also account for industry and building sector developments, such as the adoption of heat pumps and renovations. Furthermore, the report relies on ERAA 2024 and VSM 2025 (Versorgungssicherheitsmonitoring) assumptions for capacity build-out, providing a broad understanding of the energy landscape. The Monitoring Report refers to NEP 2023 as the baseline for transmission assumptions and notes the next NEP 2025 will update milestones and capacity pathways. The Monitoring Report also treats NEP milestones as hard constraints for adequacy. If they slip, adequacy risks (LOLE, EENS) rise. NEP 2023/2025 versions are cited as the reference case for capacity and transmission assumptions. In the "Verzoegerte Energiewende" scenario cited in the Monitoring Report, a 2-year delay in the NEP milestones (especially HVDC and Hansa Power Bridge) is modeled, which significantly raises the need for controllable backup capacity.

We seek to provide a commentary on the Monitoring Report. Firstly, we establish a model for the expected trajectory of German energy demand, supply, and the consequences for pertinent parameters like curtailment and EENS. We also model additional hypothetical scenarios entailing a recession and supply chain shock to illustrate how Integrated Systems planning can help Germany prepare for uncertainty and constraint outside the trilemma framework. We subsequently offer reflections on the government's 10-Point-Plan, including considerations of how to expand and adapt them to the Integrated Systems approach.

Honest demand assessment

The Monitoring Report declares the criticality of an honest demand assessment, but it also demonstrates the uncertainty in the range of its demand scenarios, ranging from 530 TWh to 910 TWh in 2030. To support a more concrete prediction of demand, GE Vernova presents its own demand prediction, which anticipates German demand reaching 567 TWh by 2030 and 620 TWh by 2035.

GE Vernova's methodology complements the Monitoring Report's approach by navigating within the uncertainty space mapped by the comparative study. Our demand projections are grounded in a rigorous internal methodology that utilizes internal assessments and data analysis, providing a concrete trajectory for the German energy landscape. We drive our forecast of additional load from the electrification of heat and transport sectors, using technology uptake modeling and establishing a relationship between historical demand in each sector and economic indicators. This allows us to forecast future annual demand using population growth and GDP forecasts. For example, our analysis suggests that electricity demand from established sectors is expected to remain stable with a small year-on-year growth of about 0.2%. Additionally, we use historical hourly load profiles, combined with future demand and peak load, to inform our projections. In the transport sector, we utilize historical EV growth to fit a logistic function, projecting future additional load from transport, and in the heat sector, we use historical Heat Pump (HP) adoption to forecast future additional load. In terms of modelling topography, Germany is modelled as part of Central Western Europe. This includes disaggregated generators in France, Netherlands and Belgium. All dispatchable thermal and hydro power plants and offshore wind farms are modelled as individual units while solar and onshore wind farms are aggregated by zone. Whereas the WindSeeG (Windenergie-auf-See-Gesetz) calls for 30 GW of offshore wind by 2030, 40 GW by 2035, and 70 GW by 2045, we have adjusted our models to be more in line with the delayed build-out and assume ~16.8 GW by 2030, ~42 GW by 2040, ~49 GW by 2045.

GE Vernova produces and maintains in-house electricity market models for various countries worldwide using industry-standard optimization software. These models are designed for expansion planning and economic dispatch. For this study, our Central Western Europe model was used specifically focusing on Germany. We model Germany itself zonally, splitting the country into 4 zones: Northwest, Northeast, Central and South (see Figure A). Interconnectors between Germany and neighboring countries are modelled using physical capacities of the transmission lines considering seasonal variations. Zonal transmission limits between the Central and South zones are modeled, including the commissioning of Sued-Ost and SuedLink in the late 2020s. Interconnection expansion includes projects currently under construction, better ensuring that the model aligns with the current trajectory of HVDC construction.

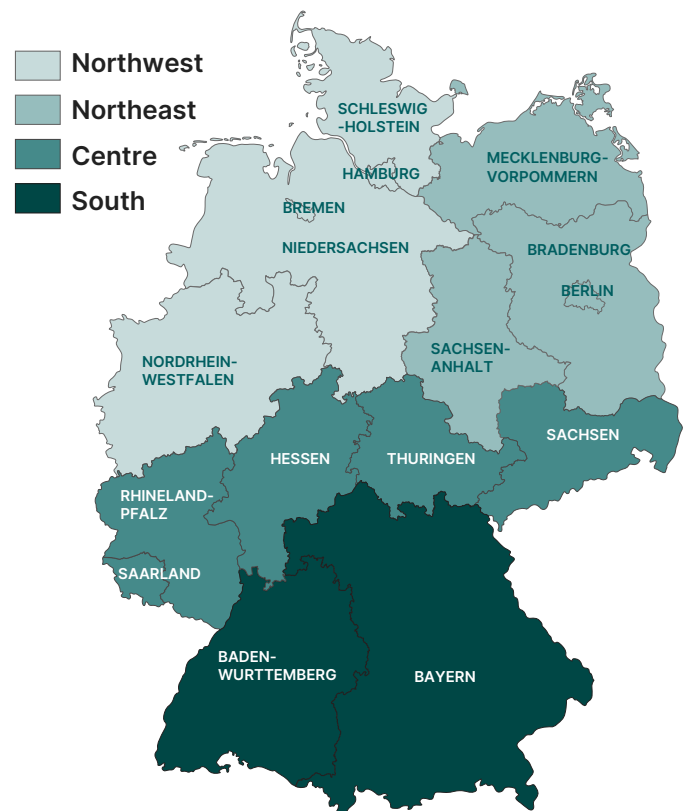


Figure A. Zonal view of Germany



Electrolysers are not explicitly included within the scope of this paper. However, for the purposes of this analysis, we assume hydrogen cost will be set by the production cost for blue hydrogen at approximately three times that of natural gas. It is assumed that additional electrolyser capacities, along with associated renewable energy sources and storage systems, will be required beyond what is currently modelled. This aligns with the European Union's directives on hydrogen and the requirements for guarantees of origin.

The model incorporates a comprehensive array of technical, economic, and policy constraints. It is first run using our capacity expansion modelling software to help optimize the capacity and timing of future capacities while minimizing total system cost. This is followed by executing a unit commitment and economic dispatch model to gain insights into the generation of these capacities and assess whether the system can meet its constraints.

Key input parameters include, but are not limited to, electricity demand projections, carbon targets/prices, and variable renewable generation profiles based on the 2021 weather year. The outputs provide up to hourly granularity, offering insights into future capacities and generation, curtailment, system reliability metrics, cross boarder flows and other economic indicators. This range of outputs produced by the various scenarios also illustrates how these factors might differ when input parameters are adjusted.

By providing a detailed and nuanced understanding of the market, GE Vernova's demand forecast is a valuable tool for stakeholders who want to stress-test a specific scenario within the uncertainty space mapped by the Monitoring Report. Our analysis reveals that electrification of heat will lead to an extra 34 TWh of demand by 2030, with heat pump profiles exhibiting strong seasonality and higher load in winter. The accuracy of our demand forecast is supported by our rigorous methodology and data analysis, making it a reliable representation of the German energy landscape. By combining projections from historical load data and economic indicators, we offer a distinct perspective on the German energy landscape, one that leverages our internal expertise and data analysis to provide a comprehensive and accurate picture of the market. This complements the Monitoring Report's approach, which provides a broad overview of the uncertainty space, and together they offer a toolkit for understanding and navigating the complexities of the German energy landscape.

The expected capacity buildout model shows the significant contribution that the addition of data centers and electrification via electric vehicles and heat pumps has on the grid. This can be seen in Figure B. While the Monitoring Report focuses on the importance of accurate projections of wind build and HVDC build out, this highlights how monitoring data centers and electrification, on top of the consequences economic growth might have on demand, will have outsized effects on the evolution of the energy sector.

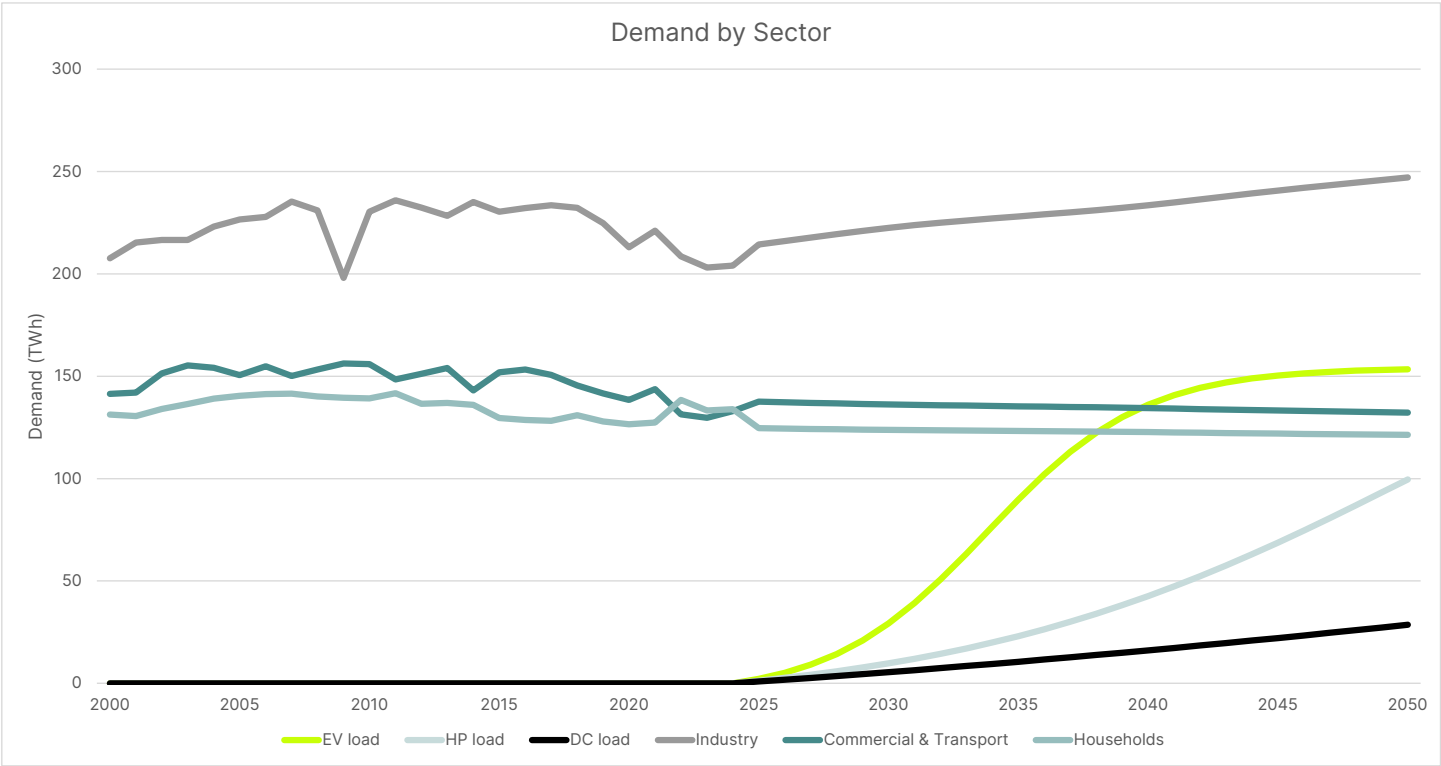


Figure B. Demand by sector in the German economy.

To buttress the detailed picture such a model can contribute to holistic energy planning, our calibrated model also produces a picture of curtailment, line loading and EENS amongst other parameters. This is based on projected technoeconomic input parameters such as demand, technology availability, cost, and carbon targets to name a few. The results paint a picture that the German grid is bound to experience many challenges with curtailment and EENS in the coming two decades. Curtailment rises to ~10 TWh by 2030, >45 by 2040, >100 by 2050, which amounts to 2.6% in 2030, 8.3% in 2040, and 16% in 2050. EENS rises to ~1,500 GWh in 2040 (see Figure C).

We also modeled other particularities of the German grid. In Figure E, we see how the addition of variable renewable energy (VRE) oscillates between under 10% and over 90% of energy generation on the grid across 2025. We can also see

how spikes in VRE are correlated with spikes in curtailment, and indeed high levels of renewable penetration can cause grid instabilities, requiring the buildout of synchronous condensers and battery infrastructure to stabilize the systems. The German grid also experiences a large amount of load flow between its energy rich north, where there is a significant amount of offshore wind, and the more energy constrained south. Something like a supply chain shock can have significant impact on that load flow, as per Figure F (which shows three modeled scenarios—an expected capacity buildout case, a recession where demand drops, and a supply chain shock where build out of renewables becomes infeasible). These are nuances and constraints for which Integrated Systems Planning is well suited. It is the most appropriate type of tool to work through these different scenarios that stand outside the narrower Energy Trilemma paradigm.

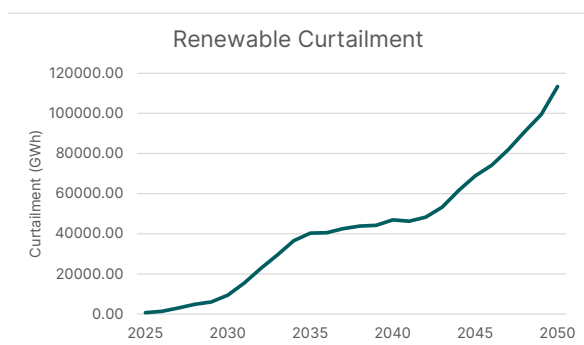


Figure C. The level of curtailment in GWh projected in Germany until 2050 under an "expected buildout" economic scenario.

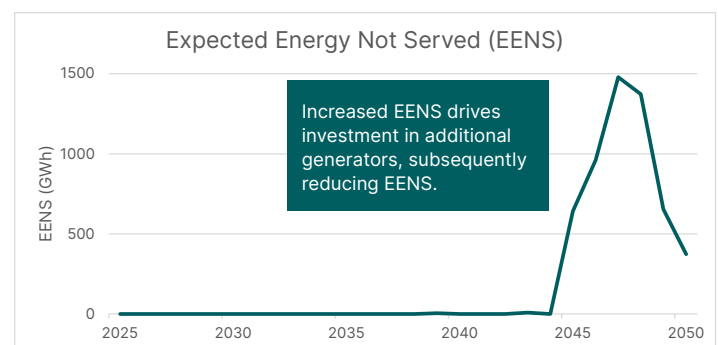


Figure D. Projected EENS in GWh in Germany until 2050 in an "expected buildout" economic growth scenario, which is illustrative of constrained build-out or delayed flexibility assumptions.

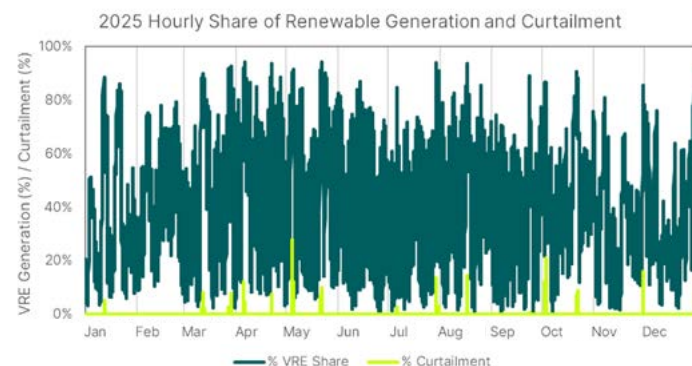


Figure E. VRE Generation and Curtailment for our "expected buildout" model across 2025. We see the correlation between the two parameters.

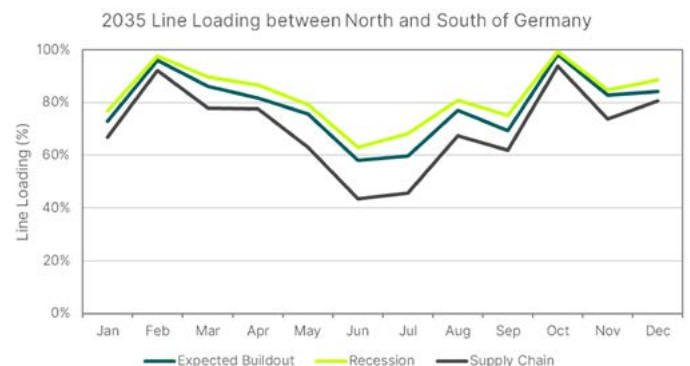


Figure F. The projected line loading between North and South of Germany in 2035. Note the dip that occurs in the event of a supply chain shock that cuts off renewables to the country.

Grids/flexibility

The Monitoring Report and accompanying 10-Point-Plan make a number of calls for accelerating planning, permitting, and supply chain processes, in order to ensure that renewable deployment remain in accordance with the EEG. We agree with this aim and call for an abundance agenda in Germany energy policy.

The Monitoring Report highlights the importance of meeting key milestones, such as the rollout of high-voltage direct current (HVDC) projects, offshore wind grid connections, and distribution grid expansion, to ensure the reliability and stability of the grid. The 70% interconnector rule, an EU requirement, is also crucial for Germany to benefit from EU adequacy and imports. The report notes that delays in commissioning these projects can directly reduce security of supply and increase redispatch costs, emphasizing the need for a coordinated approach to integrated systems planning. **By prioritizing these policy enablers and meeting key milestones**, Germany can ensure a successful energy transition and achieve its climate and energy goals.

In terms of responsibility, the implementation of these policy enablers involves various stakeholders, including DSOs, TSOs, the regulator, and the legislature. DSOs are responsible for leading the rollout of smart meters, while TSOs play a key role in ensuring grid stability and coordinating with DSOs to manage flexibility measures. The regulator, BNetzA, is responsible for overseeing the implementation of EU regulations and ensuring that the German energy market is compliant. The legislature, meanwhile, sets the overall policy framework and provides the legal basis for the implementation of these measures. **By working together, these stakeholders can ensure that the policy enablers are effective in promoting the integration of renewable energy sources and ensuring grid stability.**

In Europe, regulatory structures are slowing down economic growth, with Germany's energy sector being particularly encumbered by a multitude of laws and directives, including the EEG, EU ETS, and the Environmental Impact Assessment Directive. The permitting processes for energy projects are complex and time-consuming, involving multiple authorities and stakeholders, while transboundary consultations for cross-border projects add further complexity and delay. Furthermore, once permits are secured, energy companies often face lengthy queues for grid connection, which can significantly delay project implementation, and requirements for public participation and reporting procedures under EIA timelines can be contentious and burdensome. To overcome

these bottlenecks and achieve Germany's build-out goals, it is essential to **streamline permitting timelines and procedures**, facilitating the development of decarbonization solutions such as wind energy, transmission and distribution infrastructure, and green hydrogen builds.

Concomitantly, we also caution consideration of the risks to supply chain Germany currently faces. This is one of the crucial lessons of the gas crisis that emerged from the Russian invasion of Ukraine. Germany pursued a policy of low-cost gas in order to secure affordable energy for economic growth, but it also bore the risks of geopolitical crisis. **Germany should not take on the same risks in its build out of renewable energy.**

Prior to Russia's invasion of Ukraine in February 2022, 55% of Germany's natural gas import came from Russia. Having quickly shifted supply chains, now 45% of imported gas come from Norway, and 45% of gas comes from the U.S., with 91% of LNG coming from the United States.⁴ Now that the majority (56.8%) of German energy comes from renewables⁵, though the supply chain for materials in the renewable energy sector is imported as well.

It is worth recalling the risks faced to underwater cables and pipelines that have arisen during the war in Ukraine. Risks to security that include infrastructure espionage, whether through software or hardware, can yield both economic consequences, direct safety dangers, and environmental impacts. As the geopolitical environment continues to be challenging and unpredictable, it is critical that Germany ensure its energy supply chains are predicated on strong partners. To obviate potential security risks, policy makers should proceed with the following decisions.

- They should identify which sectors are most important for energy security, national security, and economic competitiveness. Some of these could include the manufacturing sector, defense industry, health care sector, and critical materials sector, but it would behoove leadership to be choosy and be willing to **prioritize**, as underconstrained problems are inevitably easier to solve than overconstrained ones.
- Even though the Monitoring Report expresses opposition to subsidies and demands technology neutrality, policy should then seek to **deregulate, incentivize**, and if necessary, **subsidize** those sectors based on their **production capabilities**. This step will ensure that demand and supply in those sectors is strong and buttressed against potential economic shocks. From an energy standpoint, ensuring stable supply that can allow grid expansion to match

⁴ <https://miwi-institut.de/archives/3366#:~:text=Artificial%20Dependency%20on%20the%20United,interests%20of%20the%20German%20economy.>

⁵ <https://www.destatis.de/EN/Themes/Economic-Sectors-Enterprises/Energy/Production/Tables/gross-electricity-production.html>

demand trends will reduce EENS and curtailment risks. Taking a technology neutral approach to infrastructure in particular can also enable a transition into the supply chains needed for the energy transition. **For instance**, as recommended by the Monitoring Report, a loosening of the requirements for green hydrogen, **allowing build-up of non-green hydrogen infrastructure**, can facilitate hydrogen supply chain robustness over time.

- Policymakers should be cognizant that they will need to balance a desire to support the industries Germany needs most, dependency on foreign suppliers with the power and possibility to interrupt or suspend those supply chains, and the importance of attaining the nation's climate goals. This cognizance is how Germany can avert reliance of high-risk foreign supply chains while still achieving its aims for renewable capacity expansion, by **ensuring supply chains can be systematically acquired from lower-risk, allied countries** through friendshoring and strategic trade agreements. **Procurement guardrails** can then be put in place to enforce these priorities.

For System Operators, the key lesson in the security domain is cyber resilience. Reducing the risk of inviting cyber threats on your system cannot be done solely through scenario response exercises. Grid resiliency plans must consider supply chain risks and should be evaluated in those terms.

Taken together, these energy security demands recommend rethinking the German policy framework along two fronts.

One is to expand the scope of the ten-year network develop planning cycle. Policymakers and System Operators should anticipate longer planning cycles that align with the decarbonization planning cycles of 15-30 year time horizons. This also means broadening the view of the security risks as outlined above and the nuances they create for integrated systems planning. In accordance with this, **Germany should consider reinvigorating its Sektorenkopplung framework from the prior decade**. The concept of the Sektorenkopplung framework was to ensure integration of different energy sectors, such as electricity, heat, transportation, and industry, to optimize energy use. Returning to an updated Sektorenkopplung approach would allow planners to evaluate key sectors for their energy utilization under desired constraints across the energy system. Historically, the Sektorenkopplung was dedicated to minimizing emissions, but in theory and practice, further parameters like economic competitiveness and security factors.

Capacity market

As part of its investigation into the trajectory of the German energy sector, GE Vernova modelled the possibility of a recession, in which a demand drop occurs across all sectors of the economy. We see one result is that thermal capacity is a smaller percentage of demand than in the expected capacity buildout scenario outlined in Figure B. The upshot is that EENS and curtailment are higher than the expected buildout case (see Figure G). Such challenges present the exigency of a rapid rollout of capacity market mechanisms.

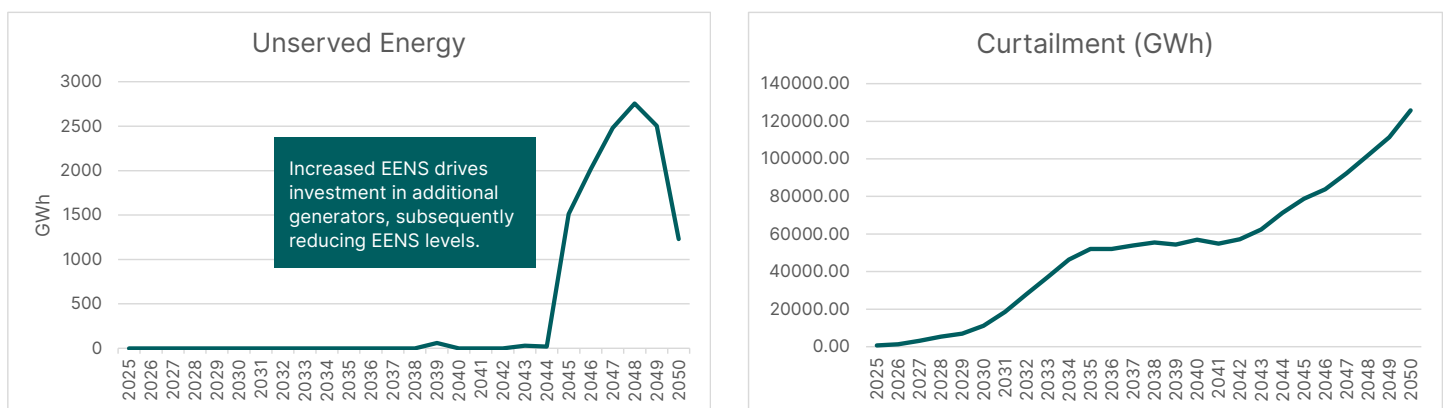


Figure G. The project level of EENS and curtailment in GWh projected in Germany until 2050 under a hypothetical recession scenario.

The implementation of a capacity market in Germany is crucial to ensure the reliability and security of the country's energy supply

The implementation of a capacity market in Germany is crucial to ensure the reliability and security of the country's energy supply, particularly in the face of its coal and nuclear exit. A capacity market can be structured in various ways, as outlined in the Monitoring Report, including a central capacity market, decentralized capacity market, capacity strategic reserve, and capacity payments model. Among these, several countries have experimented with various implementations, as per Tables 1 and 2, which demonstrate the preferability of replicating the Central Capacity Market deployed by Belgium into the German system.

Capacity Market Mechanism	Description	Country Models	Key Features
Central Capacity Market	Central authority defines total capacity need, long-term auctions for pre-qualified technologies	Belgium, UK	Central auction with multi-year contracts, de-rating, penalties for non-performance
Decentralized Capacity Market	Suppliers obligated to procure sufficient capacity to cover peak demand	France	Market-based, decentralized, emphasis on demand-side response and peak-shaving
Capacity Strategic Reserve	Volume of capacity procured outside the market, only used in emergencies	Italy	Plants in reserve not allowed to participate in energy market, keeps energy-only market intact
Capacity Payments Model	All eligible capacity providers receive regulated payment per kW	Poland	Simple to implement, but less targeted, risking higher costs if not well calibrated
Reliability Options/Hedging Obligations	Suppliers must secure financial hedges against scarcity prices	Ireland	Creates incentives for reliable availability, limiting windfall profits

Table 1. Examples of potential capacity market structures, as outlined in the Monitoring Report. A central capacity market provides long-term investment security and is a viable option for Germany

Country	Capacity Market Model	Key Features
Belgium	Centralized auctions, modeled on UK's	Direct link to European Adequacy Assessments, auctions award long-term contracts for new plants, emphasizes new hydrogen-ready gas plants
UK	Central auctions, 1 year and 4 years ahead	Competitive, technology-neutral auctions, contracts for new build can be up to 15 years, existing coal plants have participated
France	Decentralized obligation scheme	Market-based, decentralized, emphasis on demand-side response and peak-shaving
Italy	Centralized reliability options	Auctions given for reliability options with strike prices, eligibility: conventional plans, new investments, demand response
Poland	Centralized capacity market with auctions	Broad eligibility, with coal playing a central role, not a good fit for Germany due to coal dependency
Ireland	Centralized capacity remuneration mechanism	Auctions given for capacity, heavily oriented to ensuring security in an island system, not relevant to Germany due to high interconnection

Table 2. Different examples of capacity markets across Europe. Belgium's centralized auctions offer a relevant precedent for Germany's situation, as both countries are exiting nuclear power and require new firm capacity, storage, and demand-side response

A well-designed capacity market can provide Germany with the necessary investment security to attract new capacity, including hydrogen-ready gas plants, and ensure the reliability of the energy system. Taking a technology neutral approach can also promote innovation in renewables, long-duration energy storage, the ability to maintain seasonality and to invigorate hydrogen generation and capacity. The Zukunftskonzept Kraftwerksmanagement (ZKM) model, with its emphasis on bankable, multi-year contracts and technology-neutral auctions, is a promising approach for Germany's specific situation. While a decentralized capacity market can complement the ZKM by sharpening peak adequacy and unlocking demand-side response, it is unlikely to be sufficient as the primary instrument, given Germany's looming structural gap and desire for H2-ready plants. By drawing on the experiences of other European countries and adapting them to its specific needs, Germany can create a capacity market quickly (with a concept ready by 2027) that supports its energy transition and ensures a reliable and secure energy supply.

Flexibility & digitalization

GE Vernova also hypothesized about a possible supply chain crisis. Given the current reliance of German renewable energy supply, this would restrain Germany's ability to execute renewable capacity expansion without necessarily having a dramatic effect on demand. Our model shows an even more dramatic impact on EENS than Germany's current direction, with EENS approximately doubling over Germany's current projected peaks, while curtailment actually ends up being half of what we see under Germany's current expected capacity buildout direction (see Figure H). This speaks to the criticality of enhancing flexibility on the grid. In case further unexpected challenges arise for Germany's economy or society at large, there will be increasing need to manage unusual fluctuations between supply and demand through demand response, utilization of virtual power plants, microgrids, energy storage (whether through battery energy storage [BESS] or P2x technologies), smart grid systems, and other flexibility resources.

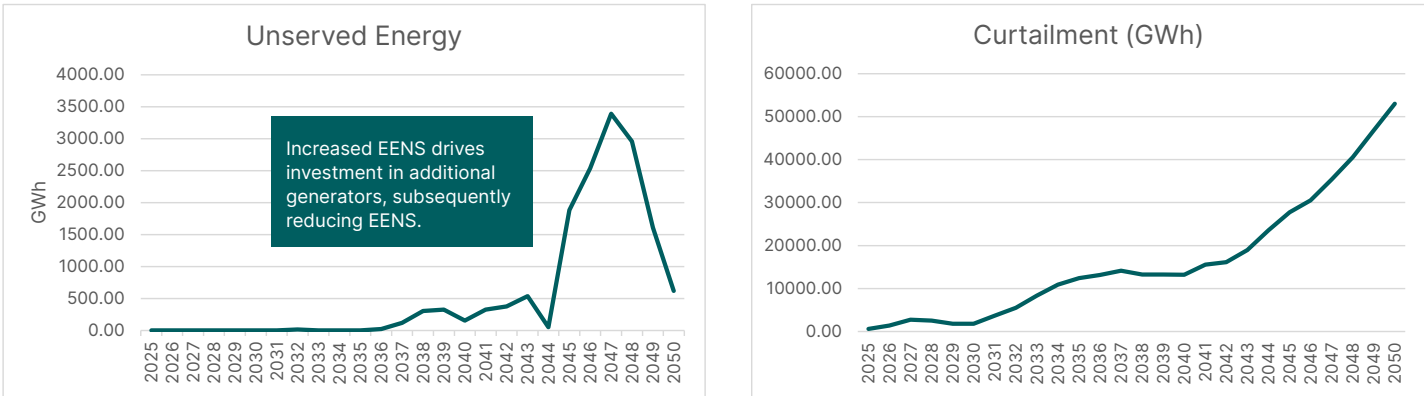


Figure H. Projected EENS (in GWh) in Germany until 2050 resultant from a hypothetical supply chain crisis.



Germany can consider implementing alternative energy market pricing systems to ensure flexibility and digitalization of the grid, but it should also tailor these goals to the need to expand market competition, lower prices, and improve market profitability. Flexibility and digitalization are linked, per the Integrated System Framework, to these other factors. Given the current state of energy technology, these three outcomes will ultimately result in an expansion of renewable infrastructure, enabling further decarbonization and enhancing energy security.

A mechanism worth consideration is developing a robust capabilities market. Specifically, these market mechanisms price for capabilities rather than capacities: inertia to slow frequency deviations, fast frequency response (FFR) to arrest frequency drops, voltage and system strength support, dispatchable flexibility from fast-ramping or peaking units, black start and restoration capabilities, and location-specific grid-forming behaviour. Relatively obscure to most energy buyers and policymakers, these crucial services can collectively be described as system attributes or essential reliability services. The core objective of capability markets is to ensure that crucial system operational services are available when and where they are needed. This requires shifting from a model that rewards availability in megawatts to one that also values responsiveness, accuracy, locational performance, and system impact. Attributes like response speed, ride-through performance, and locational value must be explicitly reflected in pricing and qualification criteria. These approaches not only reduce system costs through greater efficiency and innovation, but also enhance resilience in increasingly weather-dependent and decentralized grids.

One such example is a fast frequency response market (FFR). FFR helps to maintain grid stability by quickly responding to changes in frequency, particularly in the face of increasingly variable renewable energy sources and evolving load profiles. By rapidly responding to changes in frequency, which can arise from sudden shifts in generation or load, FFR plays a vital role in preventing blackouts and mitigating the risk of widespread power outages. The swift action of FFR helps to counteract frequency deviations, thereby safeguarding the integrity of the grid and ensuring a stable supply of electricity. Moreover, the introduction of an FFR pricing schema would create a financial incentive for the integration of more renewable energy sources and BESS into the grid, which would serve as a buffer against grid variability and help to smooth out fluctuations in frequency. This, in turn, would lead to improved power quality, as the impact of frequency

deviations on the grid would be minimized, resulting in a more reliable and resilient electricity supply. Ultimately, the establishment of FFR markets would significantly enhance the grid's ability to respond rapidly to disturbances, preventing cascading failures and further bolstering grid security, which is essential for maintaining the overall stability and efficiency of the electricity system.

As inverter-based technologies advance and grid-forming controls are becoming common, the fast frequency response market may evolve into an inertia market, incentivizing and deploying virtually instantaneous energy injection to counter frequency excursions caused by large generation or load loss. Inertia provision from both synchronous machines and grid forming inverter-based resources equally qualify for providing this grid-supportive service. Germany has successfully deployed grid forming technology through static synchronous compensators (STATCOM) and HVDC technologies today and may consider additional resources such as grid-forming BESS and eventually grid-forming wind generation as it becomes available. Germany's VDE-FNN requirements for grid-forming HVDC, power park modules and STATCOMs set the pace for rapid deployment. Other areas, such as Great Britain, Australia and Texas are also incentivizing grid forming control technology through market mechanisms and requirements.



Other market mechanisms that can be used include nodal pricing and scarcity pricing, which have been successfully implemented in the United States to rapidly expand renewables deployment and simultaneously ensuring low prices via competition and economic growth.

The Monitoring Report does not advance nodal pricing; political and equity concerns remain, though it should remain on the menu of options for efficiency and competitiveness. The use of nodal pricing leads to a more efficient allocation of resources, as it considers the true cost of generating and transmitting electricity at each node in the grid, leading to improved use of resources through financial incentive for generators and loads to optimize their behavior. Consequently, generators and loads are more likely to adjust their output and consumption based on the marginal cost of generation and transmission, which helps to reduce waste and improve overall efficiency. Nodal pricing also brings increased transparency to the grid, as it reflects the true cost of electricity at each node. Market participants are therefore better equipped to make informed decisions about their behavior, which can help to promote competition and reduce market power. Congestion is better managed with nodal pricing, as it provides a financial incentive for generators and loads to reduce their output or consumption during periods of high congestion. By doing so, the risk of grid overload is reduced, and the reliability and flexibility of the grid is improved, ensuring a more stable supply of electricity. These benefits outweigh the societal challenges associated with nodal pricing implementation.

The implementation of scarcity pricing, likewise, can have a positive impact on the reliability and stability of the grid, particularly during periods of high demand or low supply. When scarcity prices are in effect, generators are incentivized to produce more electricity, while consumers are incentivized to reduce their demand, helping to balance the grid and prevent widespread power outages, especially during periods of high stress on the grid. Providing a financial incentive for generators and consumers to respond to scarcity conditions can help to drive investment in technologies to further enhance grid stability.

Policy enablers play a crucial role in facilitating grid flexibility and digitalization. For instance, variable tariffs activate price-based flexibility, allowing consumers to adjust their energy consumption in response to price signals. In contrast, §14a controls activate network-oriented control, enabling the direct

control of controllable loads for grid balancing. Additionally, aggregator access and direct marketing activate aggregator-based and generation-based flexibility, respectively, by allowing third-party aggregators to manage flexible loads and generators to sell their excess energy directly to the market. By leveraging these policy levers, Germany can promote the integration of renewable energy sources, reduce peak demand, and alleviate grid congestion.

The rollout of smart meters is another important policy enabler, with DSOs responsible for leading this effort. The German Monitoring Report emphasizes that the rollout of smart meters should be ambitious, accelerated, and at least cost-neutral for consumers, to ensure public acceptance and avoid resistance to smart meter changes. The rollout of smart meters will also enable the mass-market adoption of small PV systems, allowing them to participate in balancing and wholesale markets. This marks a shift from the traditional fixed feed-in tariffs to a more market-based integration of distributed renewables. To fully harness the potential of this shift, it is essential to establish standardized APIs, which will facilitate seamless communication and data exchange between different systems and stakeholders. Moreover, the implementation of aggregator settlement mechanisms will help ensure that the benefits of smart metering are equitably distributed among all parties involved, from consumers and prosumers to grid operators and energy traders.

Research & innovation

The Monitoring Report emphasizes the importance of expanding R&D to cut costs and enable scaling. It calls for a focus on digitalization, AI, and electrification, leveraging new technologies like geothermal, fusion, hydrogen, and CCS. We encourage a focus on present day innovation needs as well.

Backup control centers for the grid is an area ripe for the deployment of new technology. Recent advancements in backup control center technology for the electrical grid emphasize improvements in reliability, security, and efficiency. Commercialized technologies like Distributed Energy Resource Management Systems (DERMS), Microgrid Management Systems, and Grid Edge Intelligence can achieve a higher percentage of controllable load, uptime, and energy efficiency. Cybersecurity solutions, including AI-driven threat detection systems, can reduce restoration time and mean time to recover in particular.

There are a multitude of innovations that will both be needed, on the one hand, and present a great opportunity for a more dynamic, flexible, robust, secure, and efficient grid. Improved controls and communications capabilities will be needed to coordinate all the new DERs, the connections to microgrids and hybrid systems, and prosumer assets. This necessitates novel communication tools, understanding of ride-through and fault scenario risks and capabilities, as well as blackstart procedures.

The management of load cycling for new assets like data centers and the subsequent consequences of gigawatts of increased load for congestion create physical risk to baseload generators. Gigawatt-scale cycles in load can create negative damping on generators, and the resonance on the rotating machines increases fatigue that can damage equipment. This will in turn affect pricing if those damages are not managed appropriately. BESS, FACTS, and other stabilization hardware and software can mitigate this through new control schema and energy management systems.

The rise of electrification means the grid will become more variable, decentralized, and multidirectional. Variability comes from the reality that renewable energy resources are uncertain, only generating power when the sun shines onto solar cells or the wind blows into wind turbines. The new mix of baseload generation from traditional energy sources and variable generation from renewables requires new means of stabilizing the grid.

The most well-known of these stabilizing technologies is BESS. BESS systems allow for the charge and discharge of energy to backfill gaps in generation. It is important to note that BESS does not generate energy on its own. It must rather be charged as a load from other forms of energy to store for later use. BESS is also time limited, as the current state of technology can only last for several hours at most, with the commercially available state of the art lasting for about 4 hours. Long-duration energy storage that can last beyond 8 hours is presently out of reach (even if innovation is to offer solutions over time). So gaps in renewables generation beyond these time windows must be accounted for when planning capital expansion of renewable systems in the present.

Batteries alone have advantages and disadvantages in their technological capabilities. Even though they ultimately can only discharge for limited amounts of time until they need to be recharged again, the fact that they can provide many minutes or hours of energy is quite useful in cases where a black start of assets is needed. BESS can also discharge energy extremely quickly and can be responsive to grid trips or faults requiring compensation. However, cycling can take a substantial toll on battery life. In cases where many

successions of charges and discharges are needed, the chemistry of the battery will degrade over time. This makes it critically important to select BESS technology from only the most advanced vendors that have sophisticated charge management technology to extend the usable lifecycle of the BESS significantly. Furthermore, BESS systems have a large physical footprint, requiring space and land for installment. The lifing and physical size of BESS add cost, which is a tradeoff of these systems.

Other equipment can overcome some of the limitations of batteries. Synchronous condensers, which are synchronous motors connected to the grid without a mechanical load, offer support to the grid, helping to supply and absorb reactive power that contributes to voltage regulation and electrical stability. Synchronous condensers have the benefit of physical inertia from their rotating masses, which can provide lasting stabilization not offered by BESS. Reactive power support is a complementary benefit as well. However, depending on the type of excitation systems used, synchronous condensers do not have the speed of response that BESS allows. To achieve this kind of speed with reactive power compensation, flexible AC transmission systems (FACTS) devices like STATCOMs can be used. FACTS devices are power electronic systems designed to enhance the controllability and stability of AC transmission networks. They manage power flow, reduce transmission losses, and improve voltage regulation and system stability. FACTS devices are fast like batteries but do not have the same cost and size footprint as BESS, although they can only operate within multi-minute time windows, unlike the multiple hours that BESS can work in.



Another key capability needed in the energy transition is the grid forming inverter, a technology that establishes voltage and frequency within a grid to mimicking the behavior of traditional synchronous generators. Unlike traditional grid-following inverters, which inject current through synchronization with the existing grid signal, grid-forming inverters establish the grid parameters themselves, allowing them to operate independently or in conjunction with other generators. This grid forming capability is crucial for the growing presence of renewable systems like wind, solar, and BESS and is also applicable to microgrids, islanded energy systems (like datacenters), hybrid energy systems, industrial applications (in a reindustrializing Europe), and backup and emergency power systems. They allow these systems to supply energy via new assets in a synchronized way with stable voltage and frequency. However, this makes them complex technology, requiring dynamic response and sophisticated controls methodology. They must be interoperable, meeting grid standards and regulatory requirements, while being scalable to meet growing needs. They therefore must be robust in design and functionality.

Renewables are of course not the only factors yielding grid expansion; the other major factor is the rise of the data center. Data centers consume an enormous amount of energy and are a major reason for present and projected load growth. Data center loads are less than 1 TWh of demand currently and are projected to grow with logistic uptake to over 29 TWh by 2050 (see Figure B). This growth must be accounted for in the future of grid planning. Data centers expose the grid to additional variability due to the AI

training process, causing gigawatts of load cycling within a matter of seconds, or milliseconds, which BESS and FACTS are well suited to address.

Data centers pose novel challenges to both the existing and new grid infrastructure. The volatility and magnitude of data center loads stand to create double-digit percent increases to electricity demand than can oscillate on and off innumerable times throughout the day. Large load cycling can be misinterpreted as a fault or trip event, triggering the UPS to activate and switch to backup power, even though the grid is still stable and capable of supplying power. The phenomena of fluctuating power demands, UPS-to-grid interactions, and the high reliability requirements of the data centers themselves can cause grid instability. The challenges this presents to managing grid operations is unprecedented. For rotating generators, these types of oscillations can cause torsional vibrations in drivetrains of turbine-generator equipment, which can lead to damage and premature wear. All such phenomena add cost for utility and consumer alike. Such GW-scale swings in load create commensurate oscillations in the power system, which requires greater need to manage these swings and minimize electrical impact. This will create downstream demand for technologies like BESS, FACTS, and synchronous condensers, which are well suited to manage these challenges. Further power electronics and electrical equipment necessary for the type of grid build-up to come include converters and cables. Just as with grid forming inverters, there are technical risks and evaluations that must be conducted to ensure compatibility with existing infrastructure, interoperability, and grid stability and control.



CONCLUSION

The German energy sector is at a critical juncture, with the country's Energiewende facing significant challenges in terms of security of supply, cost efficiency, and economic competitiveness. The Monitoring Report highlights the need for a more realistic and pragmatic approach to energy policy, one that takes into account the complexities and nuances of the energy system. The report's 10-Point-Plan, which emphasizes the importance of honest demand assessment, market-oriented renewables, and a technology-open capacity market, provides a useful framework for addressing these challenges.

In complement to this perspective, as we have presented throughout this paper, a more comprehensive and integrated approach to energy planning is needed, one that considers the whole system, including generation, demand, grids, flexibility, markets, and supply chains. Integrated Systems Planning provides a framework for evaluating the multidimensional nuances and constraints of the energy system. By taking a more holistic and systematic approach to energy planning, Germany can unlock efficiency gains, lower the cost of the transition, and strengthen resilience.

Our analysis suggests the trajectory of the German energy sector is likely to result in significant challenges, including curtailment and EENS spikes, unless urgent action is taken to address the flexibility and digitalization of the power system. The implementation of a technology-neutral capacity market, the ramp-up of digitization and flexibility, and derisking of supply chains, cyber-security, and friendshoring are all crucial steps in this regard that point to the value of an Integrated Systems Planning framework.

Germany should finalize a technology-neutral capacity market plan by 2027. This will provide a foundation for enhanced grid flexibility and resilience, allowing the country to better manage its energy resources and respond to changing demand and supply conditions. By establishing a capacity mechanism, Germany can attract investment, drive innovation, and create a more competitive energy market. A technology-neutral capacity framework will also enable the country to

take a more nuanced and adaptive approach to energy planning, one that balances the need for security of supply with the imperative of reducing greenhouse gas emissions and promoting sustainable development.

Scaling up flexibility and digitalization will be critical to Germany's energy transition, and this can be achieved by prioritizing clear KPIs such as controllable load, uptime, energy efficiency, restoration time, and mean time to recover. By focusing on these metrics, Germany can ensure a more reliable and responsive energy system, one that is better equipped to manage the variability of renewable energy sources and respond to changing demand patterns and loads like AI. Moreover, the use of advanced digital technologies, such as smart grids and IoT devices, can further help Germany to unlock efficiency gains, reduce the cost of the transition, and create a more sustainable and resilient energy system.

However, even with a robust energy transition strategy in place, Germany's energy security will remain vulnerable to risks associated with its supply chains and cyber security. To mitigate these risks, the country must safeguard its supply chains through strategic procurement and friend-shoring initiatives, which will help to reduce its reliance on high-risk countries and promote a more diversified and resilient energy system. This can be achieved by friendshoring, enforcing procurement guardrails around cyber security, and investing in domestic supply chains in key industries, thereby reinforcing a successful energy transition.

The choices Germany makes now will have far-reaching implications for the country's energy future. By adopting a more integrated and holistic approach to energy planning, prioritizing flexibility and digitalization, and addressing energy security concerns, Germany can ensure a successful energy transition and achieve its climate and energy goals. The path towards achieving this is by adopting Integrated Systems Planning, unlocking a more efficient, resilient energy future for Germany.

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