

The German Energy Transition: Too Much of a Good Thing?

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Abstract

Germany wants to take a leading role in combating climate change. The German energy policy aims for a massive expansion of electricity generation from wind and solar energy. At the same time, cross-sectoral electrification is planned. However, the current electricity system is not designed for a high level of expansion of volatile electricity generation. The transformation is not making sufficient progress. Although day-ahead electricity prices do not include the main drivers of retail prices, their development indicates that the expansion of wind and solar power has already overshoot the optimum by far.

Keywords

Energy Transition, Resilience, Day Ahead Prices, System Costs, All Electric Strategy

1. Introduction

Germany aims to take a leading role in combating climate change. While the EU seeks to achieve climate neutrality by 2050, Germany intends to reach this goal by 2045. A cross-sector electrification strategy with a strong expansion of renewable energy plays a key role in this effort [1].

By the end of 2024, 56% of electricity consumption and nearly 63% of electricity generation in Germany came from renewable sources [2]. Wind and solar power together accounted for 47% of electricity generation [3] [4]. Current political targets aim for at least 80% of electricity generation to come from renewable sources by 2030, primarily from wind and solar power [5]. Wind and solar power generation capacity is set to increase from 151 GW (end of 2023) to 360 GW by 2030 [6].

The question of whether such a pioneering role makes sense is not to be discussed here. Instead, the issue at hand is whether the speed at which this transition

is pursued is overburdening the resilience of Germany's energy supply system.

In late autumn 2024, prolonged periods of low wind and solar generation followed one another. At times, domestic electricity production was insufficient to meet demand. The cost of electricity generation surged more than tenfold, and large amounts of electricity had to be imported [7]. This in turn had consequences for electricity prices in other countries, leading to sharp criticism from Sweden and Norway regarding Germany's energy policies [8] [9].

At the beginning of December 2024, RWE CEO Markus Krebber issued a stark warning about the risk of future electricity supply failures [10]. He was neither the first nor likely the last to issue such warnings. While large-scale, long-term blackouts are unlikely, milder brownouts (temporary regional shutdowns) and load shedding (disconnection of large consumers) are increasingly probable. However, unlike Cuba, which suffered a prolonged blackout in October 2024, Germany is highly dependent on a stable electricity supply [11]. Even short-term disruptions can have significant consequences, such as industrial relocation.

The energy policy framework operates within the "energy trilemma" of supply security, affordability, and environmental protection. Wind and solar power, despite their assumed environmental benefits, pose challenges for supply security. Electricity from these sources is intermittent, leading to persistent temporal and regional imbalances. Germany currently lacks sufficient affordable storage solutions to bridge prolonged periods of low renewable generation, such as those occurring often in autumn and winter [7]. Even a massive expansion of electricity generation capacity from wind and solar power would not fully resolve the issue. Conversely, overcapacity during periods of strong wind and sunlight can also destabilize the grid. Germany increasingly relies on electricity imports and exports to manage volatility. Imports often take place at very high prices, exports at negative prices. The Federal Audit Office (Bundesrechnungshof) [12] has cast doubt on the Federal Network Agency's (Bundesnetzagentur) [13] claim that electricity demand can be securely met between 2025 and 2031. The Federal Audit Office is an independent authority, whereas the Federal Network Agency is in fact a subordinate authority of the Federal Ministry for Economic Affairs and Climate Action. According to the Federal Audit Office, grid expansion remains significantly behind schedule, with 6,000 km of transmission lines delayed as of 2024. Additionally, over 93,000 km of distribution networks need reinforcement, optimization, or construction, while transformers are also in short supply [14]. The Federal Audit Office estimates a potential shortfall of 23.8 GW in controllable power generation capacity by the end of the decade [15].

The second major issue with expanding wind and solar energy is cost. Germany already has one of the highest electricity prices worldwide, which is a problem for international competitiveness.

The proponents of further expansion of wind and solar energy refer to the so-called merit-order effect, as wind and solar power have the lowest marginal costs. For this reason, an expansion of wind and solar energy should push down wholesale electricity prices [16] [17]. However, critics highlight the different volatility

of electricity, generated by wind and sun. High system costs are required to integrate volatile electricity generation into the grid, which is designed for a high share of dispatchable power generation [18]. Among others, these costs include grid expansion, backup power plants with guaranteed returns (“Kapazitätsmarkt”), storage solutions, additional transformers, redispatch measures, frequency control, voltage support, negative electricity prices, potential future market restructuring in different price zones and also private costs of consumers, due to the adaptation to an increasing volatility of electricity supply.

System costs have risen steadily: network congestion management costs alone increased from €1.5 billion annually in 2017 to an estimated €6.5 billion per year in the near future. Grid expansion is projected to cost over €460 billion by 2045 [19]. Importantly, these and other system costs are not fully reflected in electricity bills; instead, they are partially covered through taxes, subsidies, and special funds [20]. Otherwise, electricity prices in Germany would be even higher. On the other hand, part of the system costs has the characteristics of overhead costs and is also partially allocated to dispatchable power generation.

The federal government did not provide an investment cost estimate for the energy transition so far, even though it is ultimately intended to lead to an “All-Electric” system [21]. Due to the lack of cost transparency, the total costs of volatile power generation are currently not reliably determinable. For the distribution of system costs across the expected higher electricity consumption in the future to have a cost-reducing effect, electricity consumption would need to increase at a higher rate than system costs. However, this is an unlikely scenario [22]. Thus, when considering system costs, without regulatory mechanisms (such as priority feed-in for renewable energy and subsidies through the Renewable Energy Act—RNA) and cost burden shifting, volatile electricity from wind and solar would not be competitive with steady power generation. Otherwise, all these measures would be unnecessary.

Given the growing costs and challenges, some key questions arise: What is the optimal share of volatile renewable energy sources in the electricity mix? Has Germany already surpassed the efficiency threshold for wind and solar expansion? Is the energy system sufficiently resilient? Does the current expansion satisfy the “magic triangle” of the energy policy, which requires simultaneous attention to security of supply, pricing and environmental protection? And finally: Can German energy policy serve as a model for other countries? The existing studies provide at best partial answers to these questions.

A significant portion of the available research identifies expansion potential for electricity generated from wind and solar power. However, the issue of system costs driven by the volatility of this type of electricity regularly plays only a secondary role. For instance, a study conducted by the German Institute for Economic Research (DIW) in 2024 acknowledges the systemic integration of renewable energy as a “challenge” but does not analyze its costs in greater depth [23]. Similarly, a study by acatech/Leopoldina/Academies Union from 2022 also

touches on this issue without a detailed examination of the associated system costs [24]. A 2022 study by KfW Research, in light of climate targets, identifies a massive need for expansion but does not address the issue of system integration and its costs at all [25]. Furthermore, many statements and studies with a similar perspective have been published by institutions that maintain close ties to the wind and solar energy lobby, such as Agora Energiewende.

Critical studies on the expansion of wind and solar energy primarily focus on land availability, particularly for wind energy [26], the environmental and health impacts of wind turbines [27], and acceptance issues [28]. While studies on the impact of renewable expansion on the resilience of the energy supply system and system costs do exist [29], they tend to remain on the fringes of the discussion.

The following aims to develop an understanding of the optimal level of wind and solar expansion at present. An analysis of the electricity exchange market provides insights. This consists of several sub-markets [30]. The EPEX Spot day-ahead market reflects real-time supply and demand dynamics. The day-ahead electricity prices include marginal costs of power generation, but exclude fixed costs of power plants, long-term system costs, network fees, and state-imposed price components such as taxes or RNA-surcharge) [31] [32]. Nonetheless, also changes in market structures—such as nuclear and coal phase-outs or renewable energy expansion—affect the direction of day-ahead electricity prices and volatility. The day-ahead market is largely free from political influence. However, there are important exceptions that will play a significant role in the following analysis, particularly the priority feed-in for renewable energies and the uniform pricing for both volatile and non-volatile electricity generation. Although the system costs cannot be quantified in this study either, we take the approach via day-ahead electricity prices. Their direction and volatility provide a valuable indication of system efficiency, supply security, and resilience against external shocks like the financial crisis, the COVID-19 crisis or the Ukraine war.

2. Methods and Data

The following analysis examines whether there is a connection between the expansion of electricity generation from wind and solar energy and the development of day-ahead prices. It is crucial that the data covers a sufficiently long period. Since 2006, data has been available in the “Energy-Charts” portal of the Fraunhofer Society [33], though only on an annual basis. From 2015 onwards, monthly data is also available, but only for electricity demand (load), not for generation. Therefore, the analysis had to rely on annual data. All price data, as well as GDP data in **Figure 1**, was adjusted to 2024 price levels to avoid distortions caused by inflation. Furthermore, it is important to avoid incorrectly attributing an increase of instability due to other causes to the expansion of volatile energy production. Although electricity was produced with lower and lower CO₂ emissions over time, CO₂ costs influenced the day-ahead-prices

in particular since 2021. Therefore, the costs for CO₂ (EU ETS) were eliminated. The analysis was conducted both with and without considering the immediate effects of the financial crisis of 2008/2009, the COVID-19 crisis (primarily 2021) and the Ukraine war (primarily 2022).

First, an overview is provided of the temporal development of electricity prices, GDP growth (as a relevant determinant of electricity demand), and the expansion of wind and solar energy (Section 3.1.).

Next, day-ahead prices are presented as a logarithmic function of the expansion of wind and solar power generation, followed by a polynomial regression analysis (Section 3.2.). The optimal expansion level was determined based on the minimum of the polynomial function. However, the small sample size (annual data from 2006 to 2024) weakens the statistical significance of the results. The calculations are explained in **Appendix 1**.

Due to the limited data set, an approximate cross-check calculation was performed using a Lagrange-based model to validate the order of magnitude of the result obtained from the polynomial regression (Section 3.3.). The corresponding calculation steps are presented in **Appendix 2**.

Finally, the volatility of day-ahead prices was analyzed as a function of the expansion of wind and solar power generation (Section 3.4.). As an indicator, the deviation of squared prices from the mean value was used.

3. Results

3.1. Overview of the Development over Time

First, **Figure 1** illustrates the expansion of volatile power generation, the development of day-ahead electricity prices, and the GDP growth rate (adjusted to 2024 prices) from 2006 to 2024 (linear scale).

It is evident that until the mid-2010s, no price-driving effect from the expansion of volatile electricity generation can be identified. The financial crisis of 2008/2009 did impact the growth of the national product, but it had only moderate effect on electricity prices, which indicates a relatively high level of system resilience at that time. From 2016 and 2017 onwards, day-ahead electricity price trend began to rise gradually. Whether this marks a trend reversal is difficult to determine from **Figure 1** at first glance. The increase was temporarily interrupted by the measures taken against the COVID-19 pandemic, only to surge significantly after 2021 due to the impact of the Ukraine war. From 2021 onwards, electricity prices increased substantially.

In 2023 and 2024, the German economy once again fell into recession. In general, since the mid-2010s, day-ahead electricity prices have been more closely correlated with fluctuations in GDP growth than before, while the overall price trend has been upward. There is a suspicion that the combination of reduced Russian gas supply, the shutdown of nuclear power plants, and the ongoing phase-out of coal has significantly decreased the controllability of electricity supply and its resilience against such shocks.

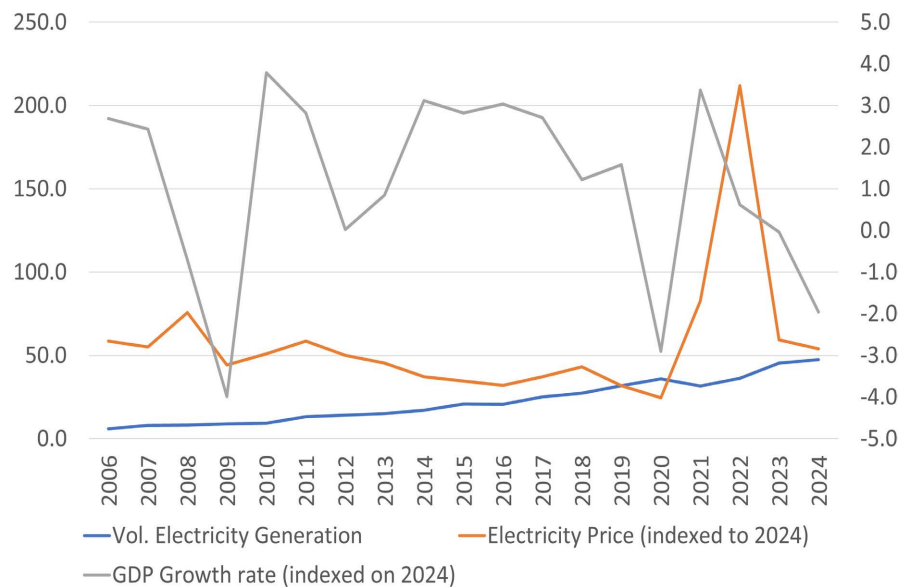


Figure 1. GDP growth rates (secondary axis), degree of expansion of volatile electricity generation and price development (adjusted) over time (data and calculations can be made available on request).

Thus, the issue of price direction and volatility is a relatively recent phenomenon.

3.2. Electricity Prices and the Expansion of Volatile Power Generation

To what extent is the price development outlined above related to the expansion of volatile power generation? To capture this relationship, **Figure 2** illustrates the day-ahead electricity prices as a function of the expansion level of volatile power generation. For scaling and normalization purposes, the data has been log-transformed (natural logarithm).

The best fit for the data points is an exponential function (**Appendix 1**). In the regression analysis of the log-transformed data, a minimum is observed in 2016/2017, at an expansion level equivalent to 23% of total electricity generation coming from volatile sources ($n = 15$; $R^2 = 0.367$). However, in this regression, price outliers from 2008/2009 (financial crises) and 2021/2022 (due to COVID-19 measures and the Ukraine war) were excluded, as they represent external, politically induced shocks. When these outliers are included ($n = 19$), the minimum is in 2014/2015 at 18%, but the R^2 value decreases to 0.106. In reality, by the end of 2024, volatile electricity generation accounts for approximately 47% of total electricity production.

A plausible interpretation of **Figure 2** is that until 2017, the price-reducing merit-order effect overcompensated for the growing system costs, to the extent that these costs indirectly influenced day-ahead prices. However, given the small sample size, these results should be interpreted with caution. If this interpretation holds, it suggests that the expansion of volatile power generation has significantly

exceeded the optimal level.

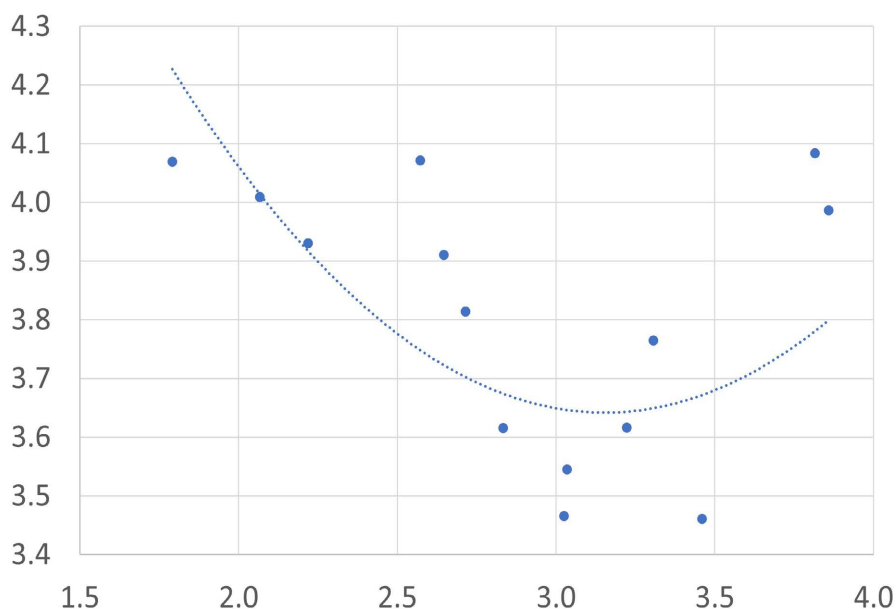


Figure 2. Price as a function of the expansion level of volatile energy generation, log-transformed (without 2008/2009 and 2021/2022; data and calculations can be made available on request).

3.3. Cross Check Calculation

Given the limited number of available annual data points, the optimal expansion level of volatile power generation of approximately 18% to 23% is cross checked below by using a model, which is based on a Lagrange approach. First, the marginal rate of technical substitution is calculated (**Appendix 2**). Under cost minimization, this rate should correspond to the price ratio between volatile and steady electricity generation.

In reality, however, both volatile and steady electricity are traded at the same price on the German electricity exchange—the origin of the produced electricity does not matter. Against this background, in the absence of opposing regulations such as feed-in priority of volatile electricity or subsidies, the demand for volatile electricity should actually be significantly lower than it currently is. This is the case because volatile electricity requires adjustment measures for consumers, leading to higher costs (e.g., storage, shifting production times, risk of interruption of physico-chemical processes). There are multiple methods to estimate the hypothetical decline in demand, each leading to different results. The method outline below is also explained in detail in **Appendix 2**.

Two phases are defined. The first phase ends in 2016, during which controllable power generation dominated, and the second phase extends from 2017 to 2024, during which volatile power generation gained increasing significance. Each phase lasts eight and six years, respectively (excluding 2021 and 2022). 2016 represents the actual price minimum, which occurred during the entire observation

period when major external shocks were excluded. During the first phase, the system was still able to handle the expansion of volatile power generation relatively well. However, the ability to do so diminished with the significant expansion of volatile power generation during the second phase.

An expected value was calculated across both phases and adjusted to the price level applicable in 2024. In doing so, the relative share of volatile electricity in net power generation is used as a proxy probability for price fluctuations, due to the correlation between the expansion level of volatile power generation and day-ahead electricity prices. However, dealing with this correlation is not without issues.

The Pearson correlation coefficient between volatile power generation and day-ahead electricity prices is only 0.11 (excluding 2021 and 2022) and 0.27, respectively. Moreover, due to the small number of data points on an annual basis, both correlations are not significant on a 0.10 level (two-tailed). However, monthly data for power load (not for power generation) is available for the period from 2015 to 2024, allowing for another cross-check calculation. Since the magnitude and direction of power load and power generation do not differ significantly, power load can be used as a proxy variable for power generation. On this basis, the samples include 97 monthly values (excluding 2021 and 2022) and 121 monthly values, respectively. When 2021 and 2022 are included, the correlation is only 0.11 and not statistically significant. Excluding the years of shocks 2021 and 2022, the resulting correlation coefficient is 0.23 and significant at a 0.05 level. Obviously, the elimination of the years 2021/2022 provides the more valid data. Accordingly, the auxiliary hypothesis of a certain impact of the expansion of volatile electricity production on day-ahead electricity prices is maintained, and the expansion level is used as a proxy probability for price fluctuations. This means that the probability of a price spike in the day-ahead electricity market increases as the expansion of volatile power generation progresses.

Finally, the share of each of the two phases in the total expected value is determined and the two values are compared. The share of the second, volatile phase in the expected value is 2.22 times higher when 2008/2009 and 2021/2022 are excluded. It is 3.88 times higher when these two years are included. If there were no regulations supporting the demand for volatile power generation under a uniform price, demand would have to be correspondingly lower than it is today. The corresponding calculations in **Appendix 2** result in an estimated optimal share of volatile electricity production of 29% (excluding 2008/2009 and 2021/2022) and 19%. **Table 1** provides an overview of the results.

Table 1. Optimal expansion level of wind and solar in Germany, share of total power generation.

	Elimination of 2008/2009 and 2021/2022	No Elimination of 2008/2009 and 2021/2022	Status Quo
Result of Section 3.2.	23%	18%	47%
Result of Section 3.3.	29%	19%	

Although the data do not match exactly, the overall picture still indicates that about half of the current expansion level of wind and solar in Germany is optimal.

3.4. On Price Volatility

In Germany, the expansion of volatile electricity generation has been driven forward year after year through subsidies (primarily via the Renewable Energy Act—EEG). However, although volatile and steady electricity are traded at the same price due to regulatory policies, they do not have the same quality or value. The entire system bears higher risks when supplied with volatile electricity compared to a system primarily relying on steady power generation. A notable example is the case of the steel plant in Riesa, which had to temporarily halt production during the period of high electricity price volatility in the dark doldrums of December 2024 to avoid greater losses [34].

These risks can also be quantified based on day-ahead electricity price trends between 2006 and 2024. **Figure 3** illustrates the relationship between the relative share of volatile electricity generation (x-axis) and electricity price fluctuations (y-axis). Electricity price fluctuations were measured using the squared deviation from the mean. The data is again log-transformed (natural logarithm). Obviously, there is a tendency of increasing price volatility, which correlates with the expansion of volatile power generation. Unlike the price development, however, no optimum can be identified regarding volatility. However, it cannot be ruled out that this may change in the future with sufficiently high investments in system stability, leading to a decrease in volatility.

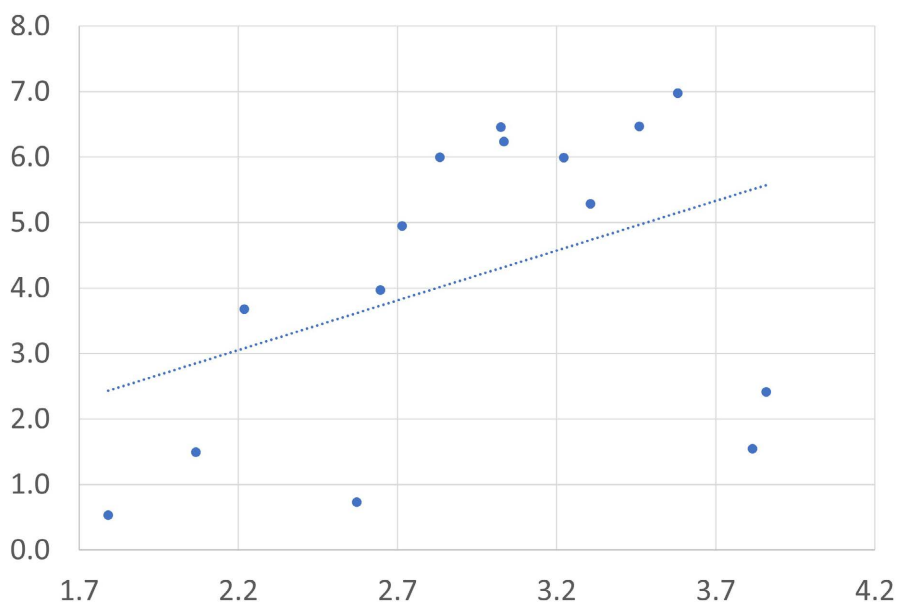


Figure 3. Electricity price fluctuation as a function of the expansion level of volatile power generation (without 2008/2009 and 2021/2022 data; and calculations can be made available on request).

In the dataset underlying **Figure 3**, the years 2008/2009 and 2021/2022 were

again excluded. The coefficient of determination (R^2) is 0.170, indicating a moderate correlation. If these four years were included, the R^2 value would decrease to 0.158. The moderate R^2 values suggest a certain success of grid stabilization measures, which have significantly increased over time.

4. Discussion

The long-term hope of Germany's energy transition relies on wind and solar power. However, the electricity system must be capable of buffering the volatility of these energy sources. Against this background, this study examined whether the expansion of volatile electricity generation (wind and solar) has already entered a suboptimal range. The indication was derived exclusively from wholesale electricity prices. The focus was on the direction and volatility of day-ahead prices, rather than the price level for end consumers.

Unlike day-ahead electricity prices, which are primarily influenced by marginal costs, end consumer prices are also determined by fixed generation costs, system costs, and government-imposed price components. In particular, system costs are expected to increase significantly in the future. Nevertheless, the direction and volatility of day-ahead market prices provide valuable insights into the development of supply shortages and system instabilities.

Due to the limited amount of data, the reliability of the regression analysis in Section 3.2 may be questioned. For the same reason, reservations must also be made regarding the approximate cross-check calculation in Section 3.3. However, although this is based on a completely different methodology, it confirms the magnitude of the regression results.

Although the reliability of the results decreases further when the data from 2008/2009 and 2021/2022 is omitted, the validity increases. This is because the results are adjusted for the influences of severe external shocks. On the other hand, the inclusion of the shock years says something about the resilience of the system.

Subject to the necessary caution in interpreting the data, the following overall picture emerges:

- The marginal benefit of expanding volatile electricity generation (as reflected in the merit-order effect) had a price-lowering impact on day-ahead prices until 2017.
- After 2017, the impact of rising system costs became noticeable.
- The apparent trend reversal in 2017 was reinforced by crises such as the COVID-19 measures (2021) and the political response to the Ukraine war (2022), but it was not caused by them.

The trend reversal starting in 2017 coincided with the gradual phase-out of nuclear power first, followed by hard coal and lignite. The increasing substitution of baseload-capable energy with volatile energy production has evidently led to a decline in resilience—also in relation to external shocks, such as the progressive reduction of Russian gas supplies to Germany from 2022 onwards.

Since the electricity supply system is still designed for a high share of dispatch-

able power generation, it became increasingly unable to absorb the subsidized expansion of volatile electricity generation. This was reflected in a continuously rising price volatility (Section 3.4.).

Even though the results must be viewed with caution given the small amount of data, it is possible that a tipping point has already been crossed in terms of systemic stability.

5. Conclusion

The calculations underlying this study focused on the economic aspects of the energy transition. While the electricity sector remains the smallest among the relevant energy sectors (transportation, heating, electricity), it takes centre stage due to the “All Electric” strategy.

The energy trilemma—economic efficiency, security of supply, and environmental sustainability—allows for compromises in cases of conflicting objectives. However, if even the broad conclusions of this analysis hold true, the current trajectory of expanding volatile electricity generation violates both the objectives of supply security and economic efficiency (affordability). Well-known German energy-intensive companies such as BASF, Stihl, Wuerth, and Covestro have drawn their conclusions and are relocating their production to other countries. The net capital outflow (direct investments) from 2021 until 2023 amounted to approximately €300 billion, driven not least by energy policy [35]. Although environmental impacts (e.g., biodiversity concerns) were not explicitly examined in this study, there is even no evidence to suggest that the energy transition, as currently implemented, has an overall positive impact in this regard [36]. This leads to only one conclusion: A temporary moratorium on the further expansion of wind and solar power generation is necessary. As things stand, German energy policy cannot serve as a model for other countries.

The optimal level of expansion of volatile energy sources is only around half of the actual expansion of 47% of the power supply (2024). However, the figure is not fixed but rather subject to change. If long-term (hydrogen-based) storage [37] [38], grid infrastructure, dispatchable power plants with guaranteed returns, decentralized energy cells (cross-sector functional units), and transformers are expanded to a sufficient extent and at an affordable cost, and if different price zones are introduced, the expansion could be resumed. In this context, the combination of grid stabilization and hydrogen production through next-generation nuclear power plants is also an interesting consideration.

Until all of this is adequately available at affordable costs, grid-forming technologies (characterized by frequency regulation, flexibility, and black start capability) must be temporarily reinforced, while grid-following technologies (primarily wind and solar) should be paused. The necessary expansion of dispatchable power generation can be achieved through various technologies, including renewable energy sources. However, biomass, hydropower, and geothermal energy are only available to a limited extent in Germany. Therefore, the discussion about

natural gas power plants with CCS technology and the reactivation of nuclear power plants, particularly Small Modular Reactors (SMRs), should not be considered taboo.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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Appendices

Appendix 1: (Related to Figure 2) Relationship between the Expansion of Volatile Electricity Generation and Price Development, Logarithmic Scale (Natural Logarithm)

By eliminating the data from 2008/2009 and 2021/2022, the following regression formula is obtained (Figure 2):

$$\ln(p) = 0.3156 \cdot [\ln(x_v)]^2 - 1.9903 \cdot \ln(x_v) + 6.7793. \quad (1)$$

Optimum calculation – first derivative:

$$\frac{\partial \ln(p)}{\partial \ln(x_v)} = \frac{0.3156 \cdot 2 \cdot \ln(x_v)}{x_v} - \frac{1.9903}{x_v} = 0. \quad (2)$$

$$\frac{\partial \ln(p)}{\partial \ln(x_v)} = 0.6312 \cdot \ln(x_v) = 1.9903 \leftrightarrow \ln(x_v) = \frac{1.9903}{0.6312}$$

$$\leftrightarrow x_v^* = \exp(3.1532) = 23.41\% \approx 23\%. \quad (3)$$

After exponentiating the optimal point (converting from logarithmic to linear scale), an optimal expansion level of volatile electricity generation of approximately 23% is obtained.

Verification of minimum—second derivative:

$$\begin{aligned} \frac{\partial^2 \ln(p)}{\partial \ln(x_v)} &= (0.6312 \cdot \ln(x_v) \cdot x_v^{-1} - 1.9903 \cdot x_v^{-1})' \\ &= 2.6215 \cdot x_v^{-2} - 0.6312 \cdot \ln(x_v) \cdot x_v^{-2} > 0 \leftrightarrow 0 < x_v < 63.64\%. \end{aligned} \quad (4)$$

Since the second derivative is greater than zero, the function has a minimum at this point. Following the same calculation method, without eliminating the data from 2020 and 2022, the minimum is found at 17.52%.

Appendix 2: Cross Check Calculation

The following considerations are based on a Lagrange approach:

Objective Function:

$$\min C = x_v \cdot p_v + x_g \cdot p_g \quad (5)$$

Constraint:

$$Y = A \cdot x_v^\alpha \cdot x_g^\beta \quad (6)$$

where:

- C represents the costs of net electricity production, composed of volatile electricity generation (with quantity x_v and price p_v) and steady electricity generation (with quantity x_g and price p_g). Prices are adjusted for inflation and CO2 costs.
- α and β are the output coefficients for volatile and steady electricity gen-

eration, respectively.

- A is a level parameter, shifting all GDP-influencing factors except electricity supply.
- Y represents the Gross Domestic Product (GDP) generated based on the described electricity mix.

By applying the Cobb-Douglas production function for the constraint, we assume that volatile and steady electricity generation are substitutable to some extent. Using the Lagrange approach (with the constraint $\alpha + \beta = 1$), we derive the following:

Lagrange Function:

$$L(x_v, x_g, \lambda) = x_v \cdot p_v + x_g \cdot p_g + \lambda \cdot (A \cdot x_v^\alpha \cdot x_g^\beta - Y) \quad (7)$$

First-Order Conditions:

$$L'(x_v) = p_v + \lambda \cdot A \cdot \alpha \cdot x_v^{\alpha-1} \cdot x_g^\beta = 0 \quad (8)$$

$$L'(x_g) = p_g + \lambda \cdot A \cdot x_v^\alpha \cdot \beta \cdot x_g^{\beta-1} = 0 \quad (9)$$

Solving for λ :

$$\lambda = \frac{-p_v}{A \cdot \alpha \cdot x_v^{\alpha-1} \cdot x_g^\beta} = \frac{-p_g}{A \cdot x_v^\alpha \cdot \beta \cdot x_g^{\beta-1}} \quad (10)$$

From equating and rearranging, we obtain the marginal rate of technical substitution (MRTS) between dispatchable and non-dispatchable electricity generation (in absolute terms):

$$\text{MRTS} = \frac{p_v}{p_g} = \frac{\alpha}{\beta} \cdot \frac{x_g}{x_v} \quad (11)$$

Intermittent electricity (“fluctuating power”) is inferior to steady electricity generation. Due to volatility risks, the hidden cost of volatile electricity supply increases by a surcharge factor $(1+z)$. Without regulations, due to the implicit costs z , the price of fluctuating electricity would have to be lower than that of evenly generated electricity:

$$p_v < p_g \quad \text{or} \quad p_v \cdot (1+z) = p_g, \quad \text{with } z > 0$$

Then, the following must hold:

$$\frac{p_v \cdot (1+z)}{p_g} = \frac{\alpha \cdot (1+z)}{\beta} \cdot \frac{x_g}{x_v} \quad (12)$$

However, the regulation creates a uniform price for both volatile and evenly generated electricity. The consequence is as follows:

$$1 = \frac{\alpha \cdot (1+z)}{\beta} \cdot \frac{x_g}{x_v} \quad (13)$$

If the demand for volatile and evenly generated electricity were not distorted by subsidies, it would have to adjust according to the relationship of the output coefficients:

$$\frac{\beta}{\alpha} = \frac{x_g \cdot (1+z)}{x_v} \quad (14)$$

The actual relative demand x_g/x_v , which is distorted by subsidies, is known. Thus, the hypothetical undistorted demand can be determined according to the relationship of the output coefficients as follows:

$$\frac{\beta}{\alpha} = \frac{0.53 \cdot (1+z)}{0.47} = 1.11 \cdot (1+z) \quad (15)$$

Thus, it is necessary to estimate the factor of the implicit additional costs of volatile electricity generation $(1+z)$. For this purpose, two phases are defined (see **Table A1**).

Table A1. Definition of phases.

	Elimination of 2021 and 2022	No Elimination of 2009, 2021 and 2022
First phase (stable)	2011 - 2016 (6 y.)	2009 - 2016 (8 y.)
Second phase (volatile)	2017 - 2024 without 2020 and 2022 (6 y.)	2017 - 2014 (8 y.)

The cutoff year is 2016, as it represents the lowest day-ahead electricity price within the observation period, free from external shocks. Both phases have the same length. To determine the expected value across both phases, pseudo-probabilities are derived from the expansion level of volatile electricity generation in each respective year. The annual values, adjusted to the 2024 price level, are multiplied by their respective pseudo-probabilities. Finally, the contribution of each of the two phases to the expected value is determined. The two values are then compared. The results are as follows (**Table A2**):

Table A2. Contribution of the first and second phase to the expected value (data and calculations can be made available on request).

	Elimination of 2021 and 2022		No Elimination of 2009, 2021 and 2022	
First phase	31.1%	13.3 €	20.5%	12.6 €
Second phase	68.9%	29.5 €	79.5%	48.9 €
Expectation	100.0%	42.8 €	100.0%	61.5 €
Relation second phase / first phase $\approx (1+z)$		2.22		3.88

The proportion of the first and second phase ratios of expected values—and thus the factor $(1+z)$ —are 2.22 (excluding 2020 and 2022) and 3.88 (including all years). Now, the ratio β/α can be determined, to which the relative demand would have to adjust without regulatory countermeasures (primarily subsidies) (see above):

$$\frac{\beta}{\alpha} = \frac{0.53 \cdot (1+z)}{0.47} = 1.11 \cdot (1+z) \quad (16)$$

A refinement of the Lagrange-based cross-check calculation could have been conducted, for example, by incorporating technical measures for demand man-

agement (such as smart meters or battery storage solutions). In this case, an increasing price elasticity of demand would have been expected both over time and as a function of the expansion level. However, the calculations performed over the observation period indicate a very low price elasticity of demand (arc elasticity), which has even shown a slightly declining trend. This suggests that other factors have overridden the expected trend. Partly for this reason, the explicit inclusion of demand price elasticity was omitted.

Accordingly, the result is as follows (**Table A3**):

Table A3. Optimal electricity generation mix (data and calculations can be made available on request).

	Elimination of 2020 and 2021	No Elimination of 2009, 2020 and 2021
Relation $\frac{x_g}{x_v}$	$\frac{x_g}{x_v} = \frac{0.53}{0.47} = 1.11$	$\frac{x_g}{x_v} = \frac{0.53}{0.47} = 1.11$
Relation $\frac{\text{Phase 2}}{\text{Phase 1}}$ (of exp. val.) = $1+z$	$\frac{29.5}{13.3} = 2.22$	$\frac{48.9}{12.6} = 3.88$
Relation output coeff. $\frac{\beta}{\alpha}$	$1.11 \cdot 2.22 = 2.46$	$1.11 \cdot 3.88 = 4.31$
Optimal generation mix	$1:(2.46+1) = 28.9\% : 71.1\%$	$1:(4.31+1) = 18.8\% : 81.2\%$
Rounded figure	29% : 71%	19% : 81%