Electricity Generation and the Energy Transition in Germany, and its Implications on the Globe

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Abstract

The energy transition (Energiewende) in the German power sector has changed the sources of electricity production, yet comparatively little attention has been paid to the quantity of electricity produced. This study examines the correlations between Germany's total gross electricity generation and (a) the generation mix and (b) electricity prices. The mix was measured in two ways: as a percentage of total generation and as output in terawatt-hours (TWh). The data comprise 12 annual observations (2005 and 2015 to 2025) drawn from AG Energiebilanzen, Destatis, the Bundesnetzagentur/SMARD, Fraunhofer ISE and other sources. Pearson and Spearman correlations were calculated in numiqo for all years and for 2015–2025 only. Total generation was negatively correlated with the renewables share ($r = -0.750$, $p = .005$) and positively correlated with the nuclear share ($r = 0.751$, $p = .005$) and the coal share ($r = 0.764$, $p = .004$). The same pattern held for nuclear and coal output in TWh ($r = 0.771$ and 0.832). Renewables output in TWh was strongly correlated with total generation in the Spearman test ($r_s = -0.839$, $p = .001$), whereas the Pearson correlation was weaker and not significant ($r = -0.554$, $p = .062$) because of the single 2005 observation. When 2005 was excluded, the correlation for both renewables measures was -0.936 or stronger in both tests. The gas share was correlated with total generation ($r = -0.691$, $p = .013$), but gas output in TWh was not ($r = -0.120$, $p = .71$), indicating that a share can capture an association that arises from its denominator. Neither the wholesale price nor the industrial price was significantly correlated with total generation. These results are associational and are constrained by a small, discontinuous sample, a strong shared time trend and a large number of tests relative to the number of observations.

Keywords: Energy, Transition, Germany, Nuclear, Clean, Electricity

Introduction

Background. Germany's Energiewende is one of the most ambitious planned transformations of a national power system. In its current form, it was launched in 2011 with the aim of replacing nuclear and fossil fuels with renewables over the following decades (Renn & Marshall, 2016). Following the Fukushima accident in March 2011, the Bundestag voted 513–79 to phase out all reactors by the end of 2022; after a brief extension during the energy crisis, the last three reactors (Isar 2, Emsland and Neckarwestheim 2) were closed on 15 April 2023 (World Nuclear News, 2023). A second law, passed in 2020, commits Germany to phasing out coal by 2038 at the latest (Clean Energy Wire, 2020). The effects are visible in the data. In 2005, nuclear contributed 27.3% of gross generation, coal 48.3% and renewables 10.2%. By 2025, nuclear generation had fallen to zero, coal had declined to 20.5% and the renewables share had more than quintupled to 56.1% (AG Energiebilanzen, 2023; Destatis, 2026). Total gross generation has also decreased, from a peak of 628.4 TWh in 2017 to 503.2 TWh in 2024, a decline of approximately 20%.

Statement of the problem. Most research on the Energiewende focuses on proportions: the growth rate of renewables, the sources that replaced nuclear power, and the effect of renewables on wholesale prices

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Available online: https://www.globalconfluencereview.in/issues/vol-1-issue-3-2026

(Cludius et al., 2014; Ketterer, 2014; Jarvis et al., 2022). Considerably less attention has been paid to the size of the total. Total generation is not equivalent to demand; it also reflects trade, and Germany became a net importer of electricity in 2023 for the first time in 20 years (Agora Energiewende, 2025). It remains unclear whether the decline in domestic generation is associated with the shift in the mix, the price increases since 2021, or both. Without such evidence, it is difficult to assess whether the transition is reducing Germany's own power generation.

Significance. Total domestic generation matters for energy security, for grid stability and for Germany's dependence on its neighbours. Industrial energy demand is also sensitive to prices: in 2022, German industry reduced its energy consumption by 9.1%, a decline that Destatis attributed primarily to high prices (Clean Energy Wire, 2023a). A national, quantitative examination of how generation moves with the mix and with prices therefore provides a useful baseline for a debate that is often argued from a single year or a single source.

Objectives. This paper aims to quantify the strength and direction of the correlations between Germany's total gross electricity generation and (a) its generation mix, measured both as shares of total generation and as generation volume by source in TWh, and (b) electricity prices, namely the day-ahead wholesale price and the industrial retail price, for 2005 and 2015–2025.

Research question. How strongly, and in which direction, are Germany's generation mix and electricity prices correlated with its total gross electricity generation between 2005 and 2025?

Hypothesis. It is hypothesized that total generation will be significantly and negatively correlated with the renewables share, significantly and positively correlated with the nuclear and coal shares, and not significantly correlated with wholesale or industrial electricity prices. It is further hypothesized that these relationships with the mix will also hold when the mix is measured in TWh rather than as proportions.

Literature Review

Theme 1: Policy changes and the phase-outs. Since the post-war period, German energy policy has shifted markedly, from strong support for coal and nuclear energy to broad scepticism towards both. Renn and Marshall (2016) attribute the major policy pivots to nuclear accidents and note that climate concerns prevented coal from simply filling the gap. Nevertheless, the share of power generated from coal did not fall immediately after 2011, and CO_2 emissions rose marginally between 2011 and 2013. The phase-out schedule has since been enshrined in law: reactors by 2022 (later extended to 2023) and coal by 2038 (Clean Energy Wire, 2020; World Nuclear News, 2023). These policies determine the direction of change in the mix but say nothing directly about the size of total output.

Theme 2: What replaced nuclear? The most robust evidence on substitution comes from Jarvis et al. (2022). Using detailed plant-level operating data, they conclude that lost nuclear output was compensated for mainly by increased coal-fired generation and higher net imports, rather than by renewables alone. They estimate the social cost of the phase-out at €3–8 billion per year, primarily as a result of air pollution. More recently, trade has become increasingly important. According to Agora Energiewende (2025), Germany became a net importer in 2023, with imports meeting around 5% of demand. The main drivers were inexpensive renewable and nuclear power from abroad at certain times, a higher carbon price that reduced the competitiveness of German coal, and the closure of the last reactors. This suggests that declines in domestic generation may reflect market decisions as well as a lack of capacity.

Theme 3: Renewables and wholesale prices. A substantial body of research has examined the merit-order effect, whereby wind and solar generation, which have near-zero marginal costs, displace more expensive plants from the market and lower the spot price. Cludius et al. (2014) estimate that wind and solar reduced German spot prices by about €6/MWh in 2010 and €10/MWh in 2012. Ketterer (2014) shows that higher wind output lowers the average price but increases price volatility. These studies treat price as the outcome variable; far fewer reverse the question and examine whether price levels vary with the quantity of a country's output.

Theme 4: Prices, demand and the energy crisis in 2022. The 2022 crisis provides a natural experiment for examining the relationship between prices and output. According to data from the Federal Statistical Office (Destatis), German industry reduced its energy consumption by 9.1% and its gas consumption by over 17% in 2022, mainly because of high prices (Clean Energy Wire, 2023a). Primary energy consumption in 2023 was projected to fall by a further 8% to its lowest level since reunification, reflecting lower output of energy-intensive products, a mild winter and continued high energy prices (Clean Energy Wire, 2023b). Because lower demand and higher imports both reduce the output required from domestic plants, prices may affect total generation indirectly through demand rather than directly.

Theme 5: Measurement problems with shares and short time series. Analyses of this kind are subject to two methodological problems. First, when one variable is a ratio that shares a denominator with another variable, the correlation between them can be spurious even in the absence of a true relationship (Kronmal, 1993). Moreover, shares that sum to approximately 100% are compositional data and therefore cannot vary independently (Aitchison, 1986). Second, two trending series can be strongly and significantly correlated even when they are unrelated (Granger & Newbold, 1974). Both problems apply directly to correlation analyses of annual national energy data.

Methods

Research design. This is an exploratory, quantitative study based on secondary data from a single country (Germany). The principal method is bivariate correlation analysis, which measures the strength and direction of the relationship between two variables without assuming that one causes the other. Because there is no comparison group and the sample is small, all results are associational and should not be interpreted as evidence that any variable causes changes in total generation.

Sample and data scope. The study covers 2005 and each year from 2015 to 2025. The intended period was 2001–2025, but a freely available annual breakdown of generation by source could not be found for 2001–2004 or 2006–2014. Because these years are excluded, the sample does not form a continuous series. Annual data were used because all variables are published annually by their sources.

Data sources and collection. Gross generation by source for 2005 and 2015–2018 is taken from AG Energiebilanzen (AGEB), the official working group on German energy balances, and figures for 2019–2025 are taken from the Federal Statistical Office (Destatis). Both report gross generation for all producers. The industrial electricity price is taken from the Bundesnetzagentur's SMARD platform (2021–2025) and from Clean Energy Wire, based on Eurostat data (2017, 2019). Day-ahead prices were obtained from Fraunhofer ISE and the Bundesnetzagentur for 2023–2025 and from Open Energy Tracker for 2015–2022.

Variables and measurements. The main variable of interest is total gross electricity generation in terawatt-hours (TWh), which was correlated with three sets of variables (Table 1). The mix shares are

defined as each source's generation as a percentage of total generation. Generation by source refers to the same four sources measured in TWh, taken from the raw generation data. These volume measures were included because the shares are calculated from total generation itself, which can produce a spurious correlation. Coal combines lignite and hard coal, and renewables combine wind, solar, biomass and hydro.

Table 1. Study variables, units, coverage and sources

Variable	**Group**	**Unit**	**Years available (n)**	**Source**
TotalGen	Main variable	TWh	2005, 2015–2025 (12)	AGEB; Destatis
NuclearShare, CoalShare, GasShare, RenewShare	Mix share	% of total	2005, 2015–2025 (12)	AGEB; Destatis
NuclearTWh, CoalTWh, GasTWh, RenewTWh	Mix in TWh	TWh	2005, 2015–2025 (12)	AGEB; Destatis
Wholesale	Price	EUR/MWh	2015–2025 (11)	Fraunhofer ISE; Bundesnetzagentur; Open Energy Tracker
IndPrice	Price	ct/kWh	2017, 2019, 2021–2025 (7)	SMARD; Clean Energy Wire (Eurostat)

Two features of the data quality should be noted. The wholesale price for 2015–2020 is not a set of annual averages but a single fixed "average" price of approximately 30 EUR/MWh applied to the entire six-year period. The industrial prices for 2019 and 2025 are point values rather than annual averages.

Procedure. The data were entered into a spreadsheet and then pasted into numiqo's online correlation calculator. Generation by source (TWh) was taken from the raw generation data, with the coal and renewables components summed. For all 12 years, total generation was first correlated with the four mix shares and the four TWh measures. The two prices were then correlated with total generation separately, since each covers different years (11 for the wholesale price and 7 for the industrial price). Finally, the mix correlations were re-estimated using only 2015–2025 to examine the influence of the single 2005 observation.

Data analysis. All correlations were calculated using numiqo (numiqo Team, 2026). Pearson's r measures the strength of the linear relationship between two variables. Spearman's rank correlation (rs) is based on the ranks of the values rather than the values themselves; it is less sensitive to a single extreme year and does not assume a linear relationship, which makes it a useful check on Pearson's r with only 11 or 12 observations. Each coefficient was tested against the null hypothesis of no correlation at a significance level of $p < .05$, and numiqo also reported 95% confidence intervals for the two-variable price tests. Because numiqo excludes any year with a missing value from a multi-variable table, variables with different coverage were analysed separately. For the 2015–2025 check, a copy of the total generation series was used with the 2005 value left blank.

Ethical concerns. This study uses only publicly available, aggregated national statistics from government agencies and research institutes. As it involved no surveys, interviews or contact with human participants, and the data contain no personal information, informed consent was not required.

Results

Total generation was most strongly correlated with nuclear and coal output and with the renewables share, and these correlations became considerably stronger when 2005 was excluded. Total generation was not significantly correlated with gas output or with either price.

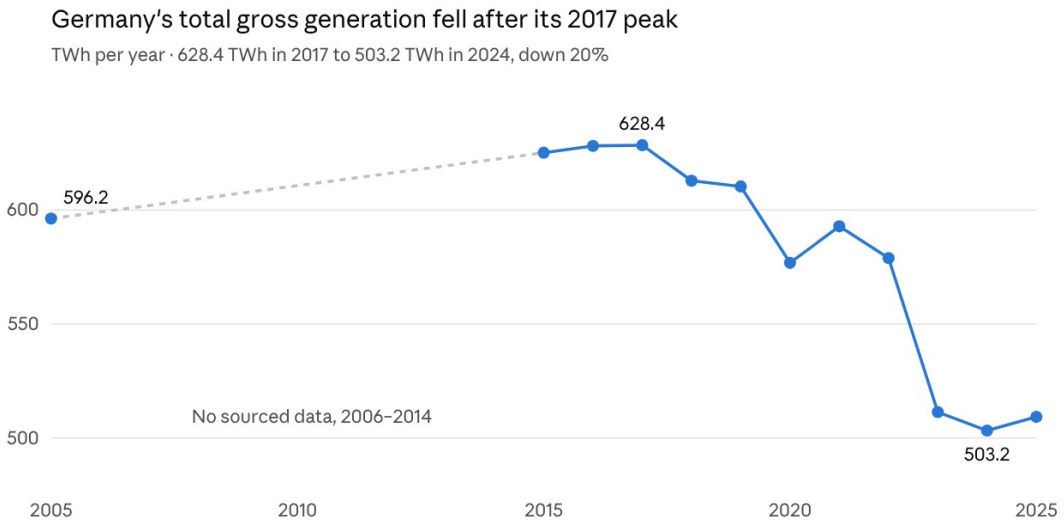


Figure 1. Total gross electricity generation in Germany, 2005–2025. Note. AG Energiebilanzen (2005, 2015–2018); Destatis (2019–2025). The dashed segment spans the years without source data.

Figure 1 shows total gross generation. Generation remained between 610 and 628 TWh from 2015 to 2019, declined in 2020 and then fell sharply in 2023, the year in which the last reactors closed. It has remained at around 505 TWh since then. Because of the 2006–2014 gap, the trajectory between 2005 and 2015 is unknown.

Generation mix for all years. All four mix shares were significantly correlated with total generation in both tests (Table 2). Years with higher nuclear and coal shares had higher total generation, whereas years with higher renewables and gas shares had lower total generation. Measured in TWh, nuclear and coal generation showed similarly strong positive correlations with total generation, slightly stronger than those of their shares. The two measures diverged for gas and renewables. Gas output was not correlated with total generation ($r = -0.120$, $p = .71$), although the gas share was ($r = -0.691$, $p = .013$). The gas share rose mainly because total generation fell, while gas output remained relatively stable at between 61.5 and 94.7 TWh in the sample. Renewables output was significant in the Spearman test ($r_s = -0.839$, $p = .001$) but not in the Pearson test ($r = -0.554$, $p = .062$).

Figure 2 explains the difference between the two tests for renewables output. In 2005, renewables generation in Germany was still low, at 60.9 TWh, while total generation (596.2 TWh) lay in the middle of the range for all years. This single observation pulls the Pearson coefficient towards zero. Because Spearman's coefficient is based on ranks, the size of the gap matters less. For 2015–2025, the points in both panels lie very close to a straight downward line.

Table 2. Correlations with total gross generation, all years (n = 12)

Variable	Pearson r	p	Spearman rs	p
NuclearShare	0.751	.005	0.809	.001
CoalShare	0.764	.004	0.825	.001
GasShare	−0.691	.013	−0.734	.007
RenewShare	−0.750	.005	−0.853	<.001
NuclearTWh	0.771	.003	0.858	<.001
CoalTWh	0.832	.001	0.832	.001
GasTWh	−0.120	.71	−0.182	.571
RenewTWh	−0.554	.062	−0.839	.001

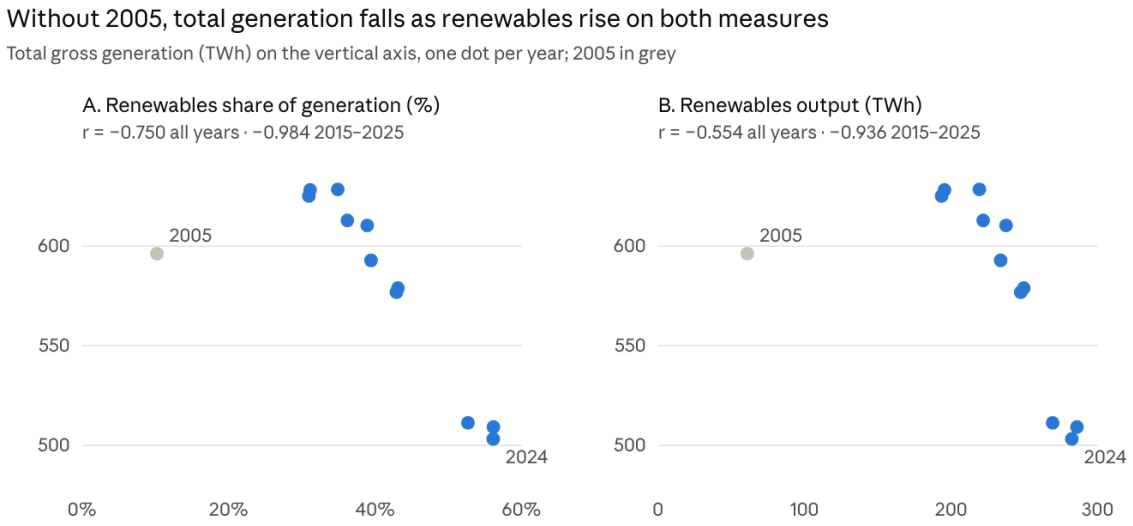


Figure 2. Total gross generation plotted against the renewables share and renewables output. Note. Sources as in Figure 1. The r values are Pearson correlations computed from the plotted points and match the numiqo output; 2005 is shown in grey.

Without 2005. Excluding 2005 strengthened almost all of the mix correlations (Table 3). The correlation for the renewables share was r = −0.984, and for nuclear output it was r = 0.970. Renewables output became significant in both tests (r = −0.936, p < .001; rs = −0.936, p < .001). Gas output remained unrelated to total generation (r = −0.0923, p = .787). Because 2005 is the only year before 2015, this check also shows how consistent the pattern has been over the most recent ten years.

Table 3. Correlations with total gross generation, 2015–2025 only (n = 11)

Variable	Pearson r	p	Spearman rs	p
NuclearShare	0.964	<.001	0.888	<.001
CoalShare	0.849	.001	0.918	<.001
GasShare	−0.699	.017	−0.782	.004
RenewShare	−0.984	<.001	−0.945	<.001
NuclearTWh	0.970	<.001	0.952	<.001
CoalTWh	0.892	<.001	0.927	<.001
GasTWh	−0.0923	.787	−0.150	.659
RenewTWh	−0.936	<.001	−0.936	<.001

Prices. Neither price was significantly correlated with total generation (Table 4). The wholesale price showed a weak, non-significant Pearson correlation ($r = -0.372$, $p = .26$) and a moderate negative Spearman correlation that narrowly missed significance ($rs = -0.590$, $p = .056$). Because six of its 11 values are identical (approximately 30 EUR/MWh), producing a large number of tied ranks, the Spearman result should be interpreted with caution. The industrial price, available for only seven years, showed no relationship in either test. All four price correlations have very wide 95% confidence intervals that include zero.

Table 4. Price correlations with total gross generation

Price	n	Pearson r	p	95% CI	Spearman rs	p	95% CI
Wholesale	11	−0.372	.26	[−0.794, 0.294]	−0.590	.056	[−0.891, 0.0732]
IndPrice	7	0.0183	.969	[−0.745, 0.761]	−0.321	.482	[−0.871, 0.586]

Relationships among the mix variables. The mix variables were also highly intercorrelated (Pearson, all years). The renewables share correlated at $r = -0.982$ with the nuclear share and $r = -0.914$ with the coal share, and the coal and gas shares correlated at $r = -0.905$. The correlation between renewables output and nuclear output was $r = -0.935$, and that between renewables output and coal output was $r = -0.829$. The two prices were also very highly correlated over the seven years for which both are available ($r = 0.977$). Because these intercorrelations are so strong, they do not indicate which component of the mix matters independently.

Limitations

This study has several limitations. First, the sample is very small and fragmented: there are only 12 observations, and the price tests use 11 and 7. With so few data points, a single year can influence a result, as 2005 does for renewables output. The confidence intervals for the price correlations range from strongly negative to positive, and the nine missing years between 2005 and 2015 cannot be examined.

Second, the mix shares are derived from total generation. Because each share is the output of a given source divided by total output, the correlation between a share and the total may be partly mechanical (Kronmal, 1993). The TWh measures were added to test this, and the gas results indicate that the problem is real: the gas share was significantly correlated with total generation, but gas output was not. The shares also sum to nearly 100% and therefore cannot vary independently of one another (Aitchison, 1986).

Third, there is a strong shared time trend. Generation fell and renewables rose while nuclear and coal declined, and most of these changes became more pronounced after 2022. Two trending series may be highly correlated even when they are unrelated (Granger & Newbold, 1974). Correlation also cannot separate the individual components of the mix, since the renewables, nuclear and coal measures have an $|r|$ greater than 0.8 with one another.

Fourth, many tests were run on few observations. Because 36 correlations with total generation were tested, one or two results at $p < .05$ may have arisen by chance. The main mix results lie well below that threshold (most $p \leq .005$), but this caution applies to borderline results such as the Spearman wholesale correlation.

Fifth, the price data are of limited quality. The wholesale price for 2015–2020 is a single approximation repeated for 6 consecutive years, so it shows very little variation over the 6 years. The industrial price covers only 7 years and includes 2 point values. The lack of a significant price correlation could therefore reflect poor measurement rather than a true absence of a price effect.

Sixth, the study includes only national annual totals and excludes demand, imports and exports. The literature identifies trade and falling demand as central to recent changes in German output (Jarvis et al., 2022; Agora Energiewende, 2025), but neither factor could be tested here.

Implications for Energy Transitions Elsewhere

The German case indicates that a rapid transition in the generation mix can be associated with a smaller domestic power sector. Other countries should therefore monitor total production, demand and trade alongside renewables shares. Because these lessons are based on 12 years of data from one country, they are offered as questions rather than predictions.

The global context. Germany is far from the only country restructuring its power system. Clean sources (renewables and nuclear) supplied 40.9% of the world's electricity in 2024, and solar generation rose by 29% to over 2,000 TWh (Ember, 2025). Several countries have followed parts of the path taken by Germany. The United Kingdom's last coal-fired power station, Ratcliffe-on-Soar, closed on 30 September 2024, ending more than 140 years of coal power (Uniper, 2024). On 18 May 2025, Taiwan closed its last nuclear reactor, Maanshan 2, and now relies on natural gas for the largest share of its electricity (World Nuclear Association, 2025). Belgium moved in the opposite direction: on 15 May 2025, its parliament voted 102 to 8 to repeal its 2003 nuclear phase-out law (World Nuclear News, 2025).

A growing proportion does not equal replacement. The renewables share in Germany increased partly because the total against which it is measured decreased. The gas results in this study show the same effect: the gas share rose while gas output changed only marginally. A country can therefore report a higher share while adding little clean generation, provided that demand falls or imports rise. Governments and analysts elsewhere should report generation by source in TWh alongside shares, so that progress in the mix is not confused with a shrinking system.

The order of phase-outs is important. Germany shut down its nuclear plants before its coal plants, and Jarvis et al. (2022) found that the lost nuclear output was largely replaced by coal and imports. Any country that retires low-carbon, always-available capacity before fossil plants faces the same trade-off between nuclear policy and emissions goals. Governments are resolving this trade-off differently: Taiwan continues to rely on gas and coal after its exit, whereas Belgium is reversing course.

The significance of a decline in output depends on how a country's grid is connected to its neighbours. Germany became a net importer in 2023 largely in response to market prices (Agora Energiewende, 2025), as power was cheaper in neighbouring countries during some hours of the day. In an integrated European market, lower domestic generation does not necessarily pose a supply risk. On an island grid such as Taiwan's, or in a country with limited interconnection, the same decline in output would require additional domestic capacity or storage.

Fast-growing economies face a different challenge. Global electricity demand rose by 4.0% in 2024, and fossil generation continued to increase by 1.4% (Ember, 2025). The German pattern of declining total output is unlikely to be repeated in countries where demand is rising. There, the challenge is not to

manage a shrinking system but to add clean supply faster than demand grows. A multi-country panel of demand and trade data would be needed to test whether the associations found here hold elsewhere.

Conclusion

This study examined the relationship between Germany's generation mix and electricity prices and its total gross electricity generation, using Pearson and Spearman correlation analyses of 12 annual observations from 2005 to 2025. The first part of the hypothesis was supported: total generation was significantly and negatively correlated with the renewables share, positively correlated with the nuclear and coal shares, and not significantly correlated with either price. The second part was only partially supported. Nuclear and coal output in TWh were as strongly correlated with total generation as their shares, but renewables output showed a strong correlation only when 2005 was excluded or ranks were used, and gas output showed no correlation at all.

These results are descriptive and do not establish causation. Renewables did not reduce output on their own. During the same period, Germany retired its remaining nuclear plants, reduced coal generation, experienced a fall in industrial demand in 2022 as a result of the energy crisis, and became a net importer of electricity. Because these changes occurred together, the renewables share serves as a convenient summary of the entire shift. The finding that price levels did not track generation suggests that, at the national annual level, the decline in output reflects structural change more than year-to-year price fluctuations, although the strength of this conclusion depends on the quality of the price data.

Future research should fill the 2006–2014 gap using the complete annual series from AG Energiebilanzen, measure generation by source in TWh rather than as percentages, and incorporate electricity demand, net imports and weather data. Monthly or hourly data would provide many more observations and allow time-series methods that address trends directly. More broadly, the findings indicate that the decline in Germany's domestic generation should be understood within the wider restructuring of its power system, and that the energy transition should not be judged by output totals alone.

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