

SWEDISH POWER PRICES HIGHER & MORE VOLATILE AFTER NUCLEAR SHUTDOWNS

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Swedish power prices higher and more volatile after nuclear shutdowns

Summary: *The shutdowns of the Ringhals 1 and 2 nuclear reactors preceded a decoupling of electricity prices between Sweden's northern and southern electricity price zones. Energy prices have risen in the higher demand zones SE3-4 by up to 141%. Increased price variability has touched all electricity price zones, with SE4 experiencing the largest increase, as measured by a 520% rise in price standard deviation.*

Analysis of generation sources' behavior patterns suggests that the lost generation of Ringhals 1 & 2 was largely replaced by wind power. Because wind generation is inherently variable (and because most new wind capacity is located far from major demand centers) this shift likely contributed to both higher prices and greater price volatility. Overall, the loss of stable nuclear generation from Ringhals 1 and 2 appears to have had a negative impact on Swedish electricity prices.

Introduction

The Swedish electrical grid is divided into four price bidding areas, from north to south: Luleå (SE1), Sundsvall (SE2), Stockholm (SE3), Malmö (SE4). The two northern zones tend to generate more energy than they consume (mostly from hydroelectric plants and wind) while the southern zones, home to Sweden's larger cities, usually consume more than they generate (mostly from nuclear power plants). According to Svenska Kraftnät, the Swedish grid operator, "boundaries between bidding areas are drawn where the main limitations are, in terms of how much electricity can pass." (Svenska Kraftnät, n.d.)



Swedish electricity price areas.
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According to the International Energy Agency, Sweden sources of electricity are hydroelectric (38%), nuclear (29%) and wind (23.5%) (International Energy Agency, n.d.). Most of the generation growth has come from onshore wind, going from 16 TWh in 2015 (around 12% of total generation) to 40 TWh in 2024 (approximately 24%).

Due to profitability and tax concerns, Vattenfall, the Swedish power company, decided to shut down the Ringhals 1 and 2 nuclear reactors: Ringhals 2 (R2), a pressurized water reactor, was shut down on December 31st, 2019 and Ringhals 1 (R1), a boiling water reactor, was shut down on December 31st, 2020. This removed around 1700 MW of stable generation capacity from the Swedish electricity grid and dropped nuclear energy from generating 53 TWh in 2015 (36% of total generation) to 49 TWh in 2024 (31% of total generation). Both reactors and two additional currently operational units, are part of the larger Ringhals Nuclear Power Plant located in the Värö Peninsula near Gothenburg, placing it in the SE3 pricing zone.

Fortunately, the drop in nuclear generation has had little to no impact on Sweden's carbon emissions from electricity generation. It has, however, had an impact on electricity prices. Using data for prices per zone and generation from the ENTSOe platform, as reported by Swedish grid operator Svenska Kraftnät from 2015 to 2024, we look at the behavior of prices and generation before and after the shutdowns of R1 and R2.

Data and methodology

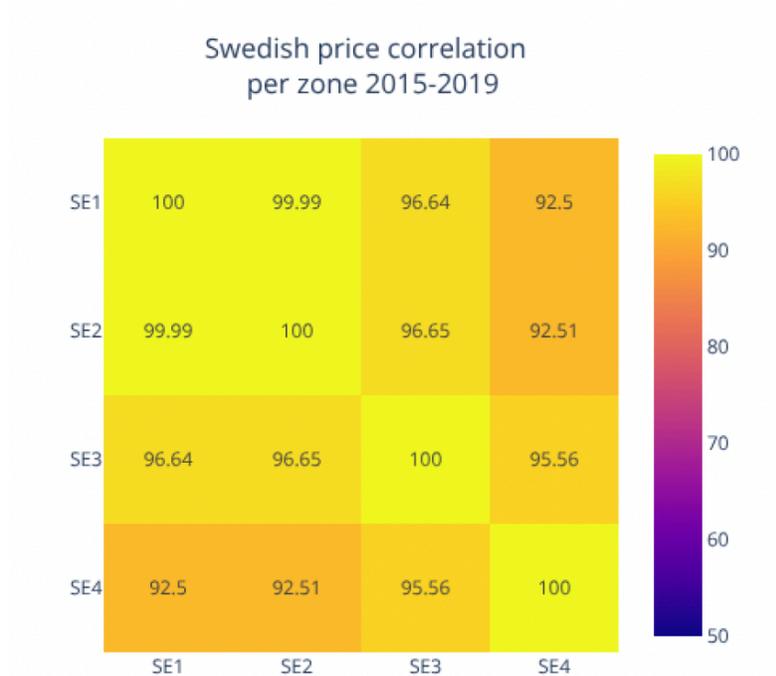
We use pricing and generation per source data for each zone and for the entire country from the ENTSOe transparency platform. Datasets are available starting from 2015 and are updated every 15 minutes. For ease of data management, we have taken datasets from January 1st, 2015 to December 31st, 2024 and resampled the dataset for hourly averages. Missing data points amounted to 12 in a 94,754-point dataset, so 0.01% and were resolved through simple linear interpolation.

Loss of nuclear generation led to price zone decoupling

In the Swedish grid, bidding areas can have different prices due to limitations of transmission lines that connect higher generation from the north to higher demand from the south. That said, prior to the R1 and R2 shutdowns prices, prices and spreads for all zones were extremely similar, as shown below:

	SE1	SE2	SE3	SE4
Mean (€/MWh)	32.63	32.63	33.08	34.16
Std (€/MWh)	12.64	12.64	13.14	14.23
Min (€/MWh)	0.12	0.12	0.12	0.12
Max (€/MWh)	255.02	255.02	255.02	255.02

Prices prior to the R2 shutdown in 2019 were very similar for all zones, suggesting minimal difficulty in balancing supply and demand nationally. Price correlations indicate a well-integrated system in which northern surplus generation reliably met southern demand:



After 2019, major external events have had a significant impact in energy markets, electricity generation and demand. The COVID-19 pandemic modified demand patterns through shutdowns that affected industrial demand and quarantines that shifted demand to residential consumers able to work from home. The Russian invasion of Ukraine heavily impacted natural gas supplies to Europe, leading to massive jumps in energy prices. Although Sweden was partially insulated from these shocks due to its high degree of energy independence, these events form an important background context for interpreting post-shutdown price dynamics.

After the shutdown of R2, price behavior per zone changed as follows:

	SE1	SE2	SE3	SE4
Mean (€/MWh)	14.42	14.42	21.21	25.87
Std (€/MWh)	11.53	11.53	19.27	20.17
Min (€/MWh)	-1.73	-1.73	-1.73	-1.96
Max (€/MWh)	189.25	189.25	254.44	254.44

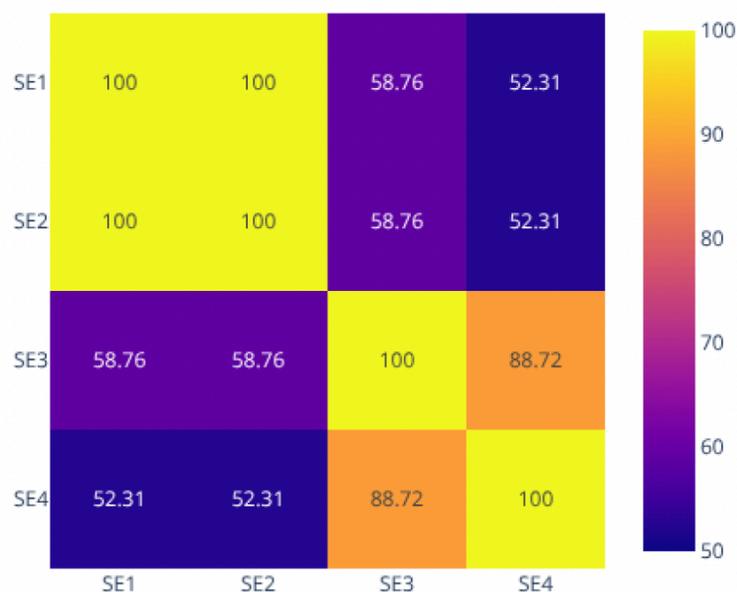
Average electricity prices declined during this period, largely reflecting reduced demand during the COVID-19 pandemic. However, a clear divergence emerges between the northern generation-heavy zones (SE1–SE2) and the southern demand-heavy zones (SE3–SE4).

- SE1–SE2 experienced price declines of approximately 56%, with only modest increases in price volatility ($\approx 9\%$).
- SE3–SE4 also saw price declines, but of a smaller magnitude (36% in SE3 and 24% in SE4), accompanied by substantially higher volatility (47% and 42%, respectively).

In other words, while prices fell nationwide between 2019 and 2021, volatility increased disproportionately in the zones that lost stable nuclear supply.

Price correlations show a clear decoupling between northern and southern price zones. Taken together, these results indicate that the shutdowns of Ringhals 1 and 2 coincided with both a persistent price divergence between northern and southern zones and a pronounced increase in price volatility, especially in high-demand southern regions.

Swedish price correlation per zone 2019-2021

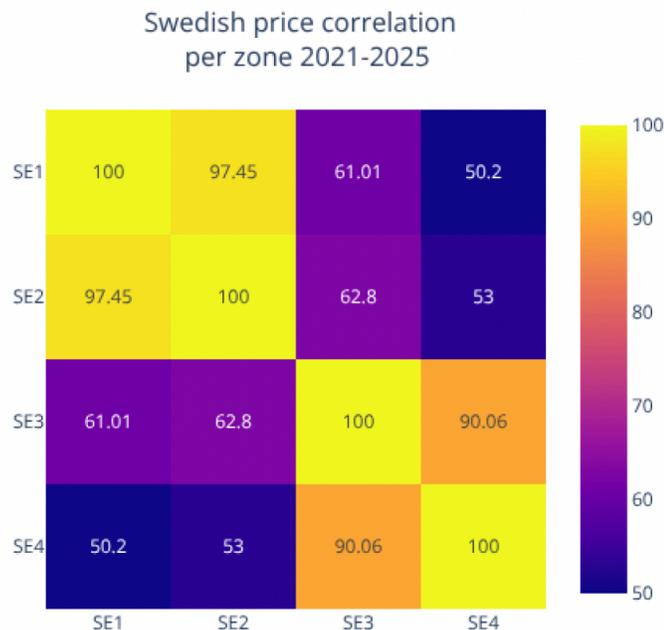


After 2021, EU countries took measures to mitigate the impact of the loss of Russian natural gas imports, mostly by switching to imports from the United States and Qatar (European Commission, 2022).

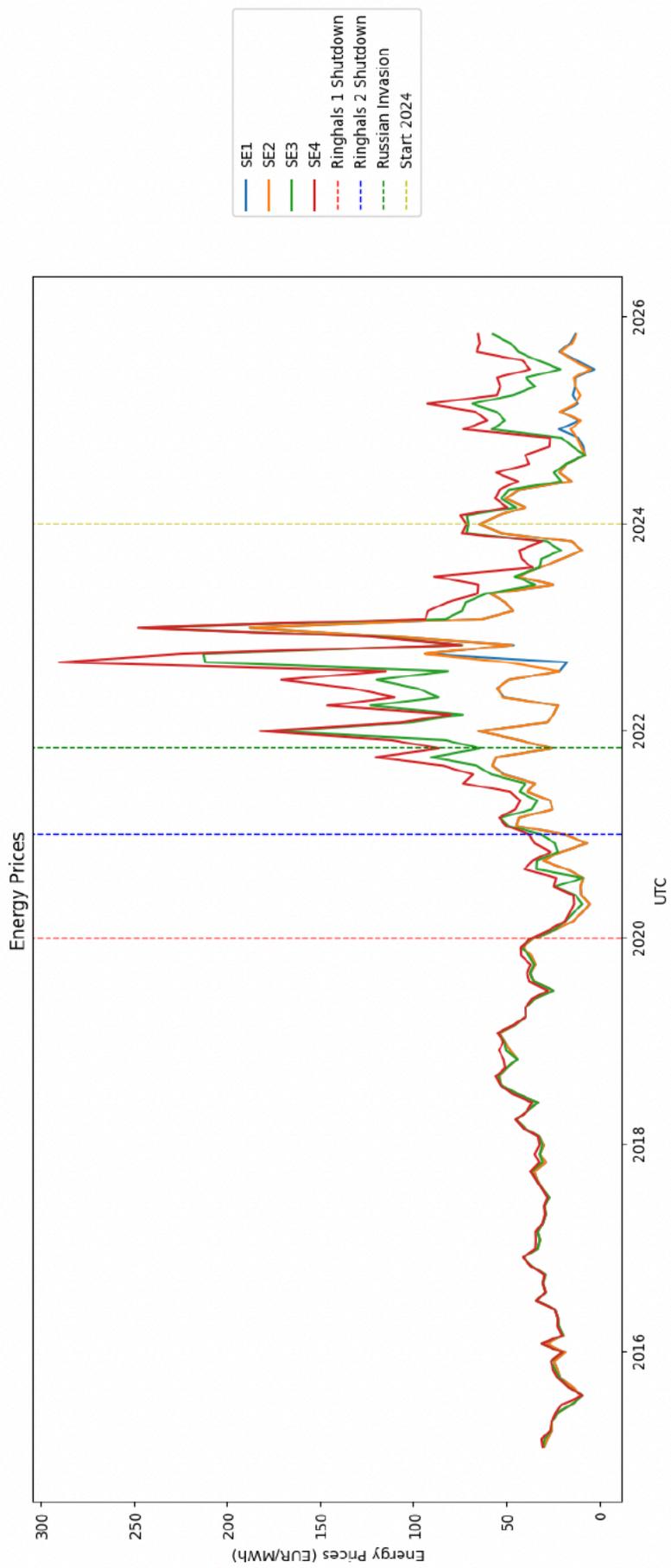
However, starting in 2021, the shutdown of R1 led to another endogenous shock to Swedish energy prices. From that date forward, energy prices in SE1-2 are around 14% higher than prior to the shutdown of both reactors while SE3 sees prices 100% higher and SE4 prices become 141% higher. Price variation paints an even starker picture: standard deviation per zone jumps for all price zones, SE1 by 270%, SE2 by 277%, SE3 by 506% and SE4 by 520%. This means that electricity prices after the shutdown of R1&2 are dramatically more unstable than prices prior to the shutdowns. We can see price behavior for the period below:

	SE1	SE2	SE3	SE4
Mean (€/MWh)	36.89	37.41	66.23	82.19
Std (€/MWh)	46.77	47.64	79.58	88.27
Min (€/MWh)	-74.11	-60.04	-60.04	-60.04
Max (€/MWh)	590	590	799.97	799.97

And price correlations show, once more, the decoupling between the north and the south:

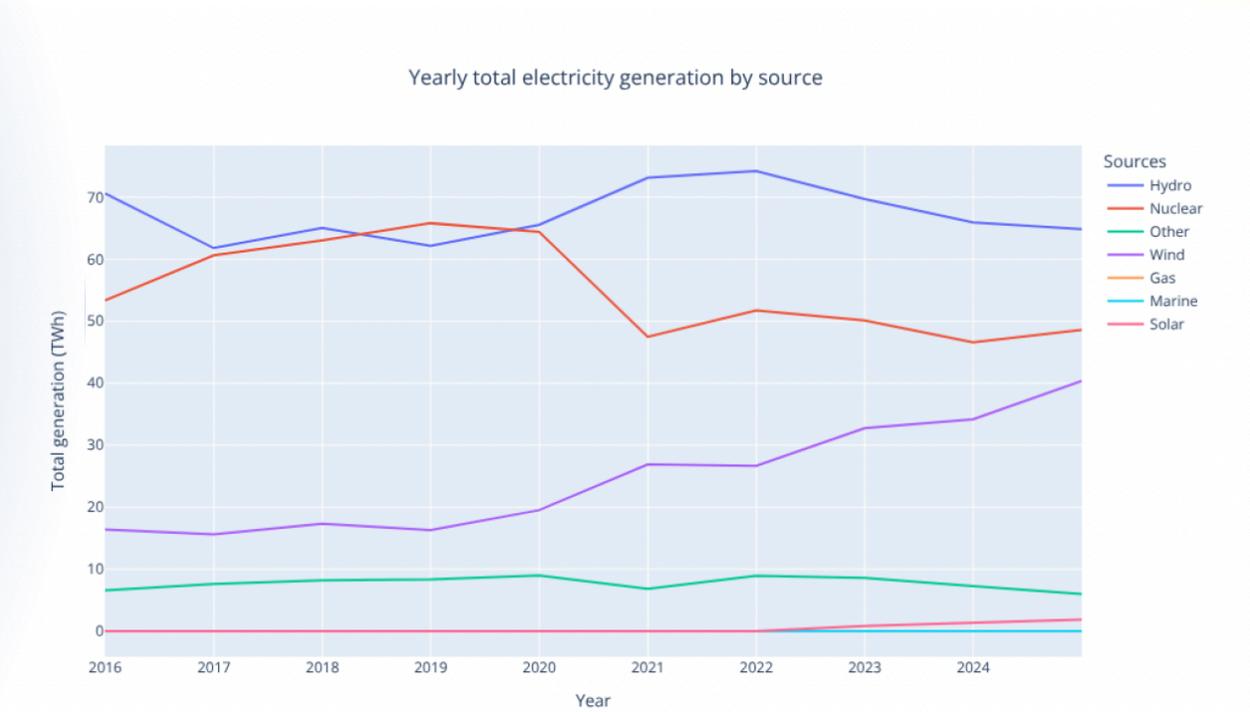


This decoupling can also be shown in the time series of prices. We can see the impact not just of the shutdowns of R1-2 but also how external factors like the COVID-19 Pandemic and the Russian Invasion of Ukraine have led to large price spikes that manifest differently for each pricing zone:



What we can see from the data is that the shutdowns of R1-2 coincide with a decoupling of electricity prices between northern price zones and southern ones. Additionally, energy prices have risen significantly in the predominantly urban electricity price zones SE3-4 by up to 141%. Price variability has touched all electricity price zones, but once again SE3-4 are the ones most heavily affected with a jump in price standard deviation of up to 520%.

These impacts could be attributed to drastic loss in generation due to the two nuclear power plant shutdowns. However, the data does not appear to bear this out: total generation has gone from 157.9 TWh in 2015 to 161.6 TWh in 2024, an increase of 3.7 TWh which broadly covers the generation lost due to the shutdowns. This leads us to hypothesize that the jump in prices and price variability may be due to issues with electricity transmission from north to south putting additional strain on the grid and unpredictability of wind generation, leading to larger price swings. We can see the change in generation per source below.

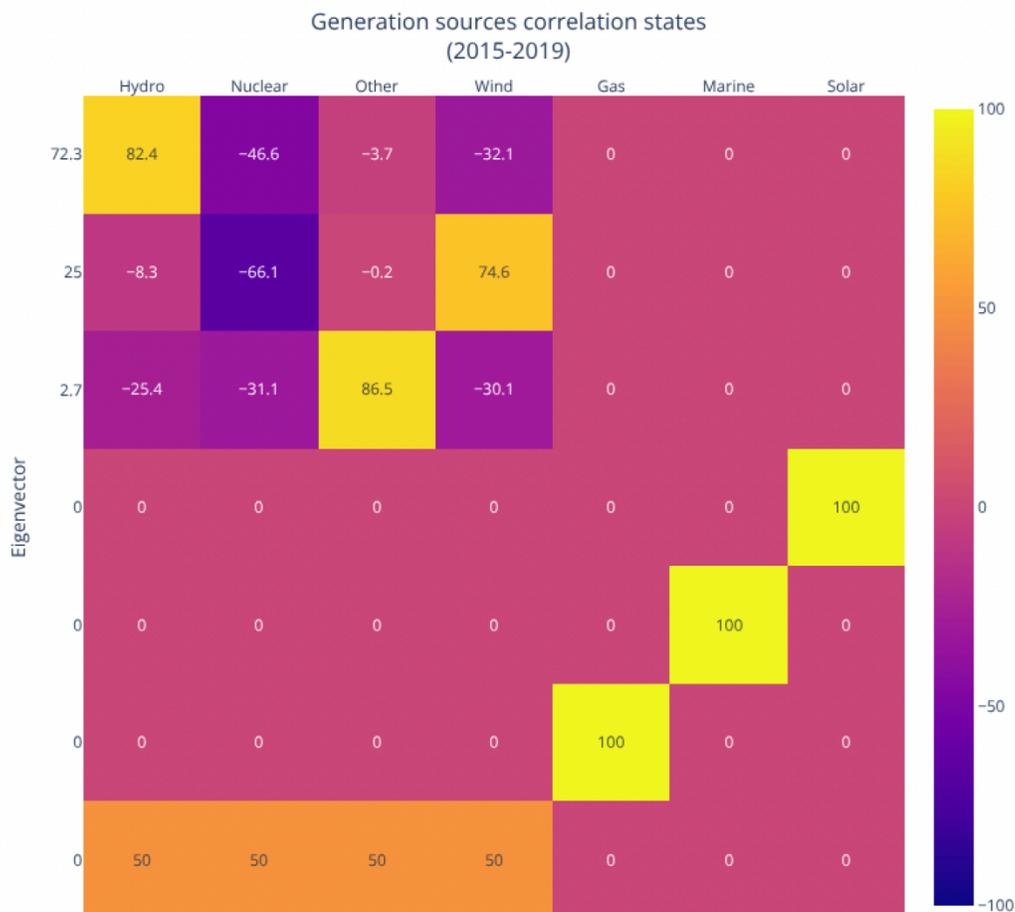


Self-states of the Swedish grid: increased impacts of wind generation

To further examine these dynamics, we analyze generation “self-states” using Principal Component Analysis (PCA). PCA identifies combinations of generation sources that explain the largest share of variance in total generation, allowing us to characterize how the grid responds to changes in supply conditions.

PCA is usually employed for dimensional reduction, but here we will use it to characterize the behavior of electricity generation of the Swedish grid before and after the shutdown of R1&2. From generation data, the method calculates the correlations between all generation sources and finds which combinations of sources account for the greatest variance in the dataset. These are reported as vectors (known as principal components) that can be understood as characteristic states of the grid, i.e. arrangements of generation sources that “come naturally” to the grid and allow for any given state of the grid to be explained as a linear combination of these “self-states” (mathematically known as eigenstates). In this way we can see how different generation sources are related to each other, which sources compensate when one drops, which are more or less significant in driving the change in total generation.

Let us look now at the self-states of the Swedish grid prior to the shutdown of R1&2:

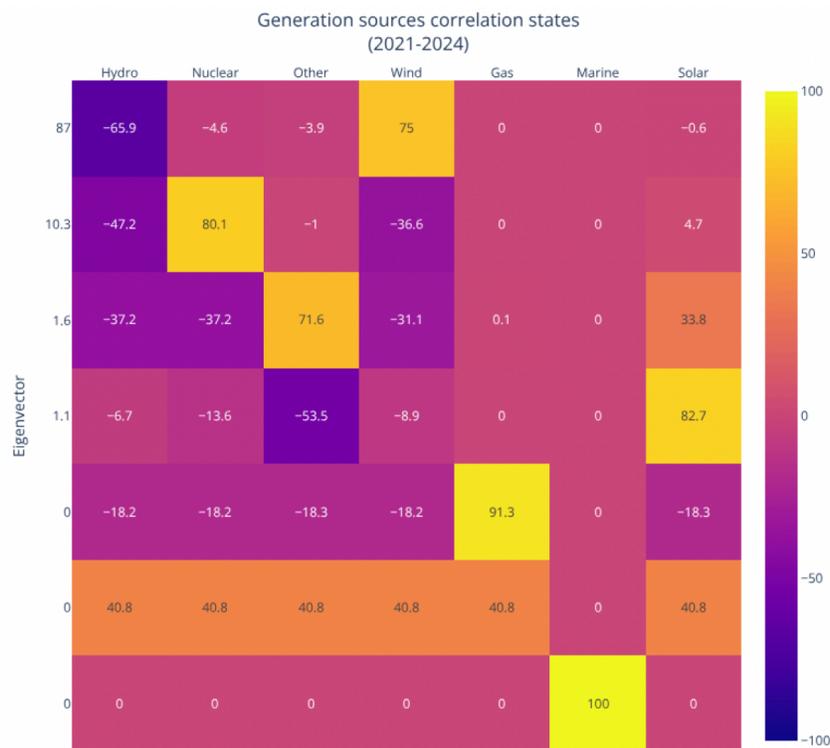


The graph above should be read in the following way: each row is a self-state or eigenvector of the grid, as we explained previously, meaning that each row is a “natural configuration” of the Swedish grid. To the left of each row, we have a label showing the amount of variance of generation that the particular state explains: the first one explains 72.3% of total variance, the second 25%, the third 2.7%, etc. The color map to the right describes the relative importance of a particular energy source to that particular self-state: the largest positive value is the most important and the main driver of variance in that particular state, positive or negative values of the remaining components show which sources are correlated or anticorrelated with that first value and by how much.

In light of the above we can then read the above plot, showing the self-states of the Swedish grid prior to the shutdowns of R1&2, in the following fashion:

- Given a standard threshold of 95% of explained variance for component analysis, we can confidently claim that the first two self-states are the only ones we should pay attention to for our current analysis since between them they account for 97.3% of the variance of electricity generation.
- These two self-states show the correlations between hydroelectric, nuclear and wind generation, the three most important generation sources in the Swedish grid, with around 90% of total generation.
- The first self-state corresponds to the following behavior: generation mostly driven by hydroelectric power, negatively correlated with nuclear energy first and then with wind. This means that hydroelectric power is the most important driver of variance of the most significant self-state, and it acts as a backstop for nuclear energy first and then for wind. In simplistic terms: when hydroelectricity generation drops, nuclear first and then wind go up to compensate and vice versa.
- The second self-state shows that wind generation is the second most important driver of generation variance with nuclear energy as its backstop. This means that, when wind generation drops, it is nuclear energy that compensates for the loss of supply.
- Looking at these two first self-states we find that a recurring pattern in the Swedish grid is that hydroelectric and nuclear generation both backstop drops in wind generation, with hydroelectric generation serving as the mainstay for the entire grid.
- The remaining self-states, accounting for 2.7% of variation in electricity generation or less, do not influence significantly electricity generation and correspond to either the remaining sources of energy generation (natural gas, marine generation and solar) or show that other sources of energy are called upon when the three main sources falter.

After the shutdown of both R1&2, the new generation self-states look like so:



We see a change in behavior, not just in terms of the self-states themselves, but in terms of the amount of variance they explain. Let us summarize the changes:

- While the two first self-states still account for 97.3% of variance, the balance has changed: now the first self-state accounts for 87% of variance, up from 72.3%.
- Again, as expected, the two first self-states show the correlations between the three main generation sources in Sweden, hydroelectricity, nuclear and wind. However, the relationships between the three have changed.
- The first self-state is now dominated by wind as the main driver of variance, with hydro being the exclusive backstop. Compared with the arrangement prior to the R1&2 shutdowns, nuclear has had an expected drop in relevance, leaving hydroelectric generation as the main counterbalance to losses in wind generation.
- The second self-state is now dominated by nuclear energy, with it serving as a counterbalance of drops in hydroelectric and wind generation. Compare with the case prior to the shutdowns where nuclear generation only counterbalanced drops in wind generation.

- Once again, looking at the two main self-states we see a significant change in behavior: wind is now the main driver of generation variance (corresponding to its rising importance to the grid) and now hydroelectric generation alone bears the highest burden to compensate for drops in wind. The R1&2 shutdowns have put falling nuclear generation in the position previously held by hydroelectricity: to backstop drops in the other two main sources. Since nuclear generation is now quite smaller than hydroelectric generation and is comparable to wind (29.3% vs 37.7% for hydro and 23.5% for wind) this puts nuclear generation in a quite disadvantageous position.
- The remaining self-states have also changed: solar energy now has joined other sources as the explanation of 1.6% of variance in generation and also gains importance as a replacement for Other sources of generation explaining 1.1% of generation variance.

The changes in the behavior of the Swedish grid we have seen above can provide some explanation for our previous results for the rise in average prices and their standard deviation: while external shocks like the COVID19 pandemic and the Russian Invasion of Ukraine may have had a major hand in changing the energy landscape of Europe in general and Sweden in particular, the shutdown of the Ringhals 1 and 2 reactors appear to have also changed the balance of energy generation of the Swedish grid in a way detrimental to prices.

The behavior of the Swedish grid before and after the Ringhals shutdowns can be summarized as follows:

Pre-shutdown self-states

Prior to the shutdowns of Ringhals 1 and 2:

- The first two self-states explained 97.3% of total generation variance.
 - Hydroelectric generation served as the primary stabilizing force, backstopping both nuclear and wind generation.
 - Nuclear generation, in turn, compensated for fluctuations in wind output.
- In effect, hydro and nuclear together provided a robust buffer against wind variability.

Pre-shutdown self-states

After the shutdowns:

- The first self-state alone explains 87% of total variance, up from 72.3%.
- Wind generation becomes the dominant driver of variability, with hydroelectric power acting as the primary (and often sole) counterbalance.
- Nuclear generation shifts into a secondary stabilizing role, despite its reduced share of total generation.

This represents a structural reconfiguration of the grid: hydro now bears a greater stabilizing burden, while nuclear—smaller in scale than hydro and comparable to wind—must compensate for variability across multiple sources.

Discussion

These results suggest that while Sweden has maintained overall electricity supply following the Ringhals shutdowns, the composition and spatial distribution of that supply have changed in ways that adversely affect prices. As wind generation has gained grid penetration, it has exposed Sweden to the supply variability intrinsic to it leading in turn to higher and less stable prices. We can see this reconfiguration of the behavior of the three main electricity sources in our self-state analysis.

The increased reliance on wind generation has also meant that electricity generation is further away from the largest centers of demand, as wind generation is concentrated in the north of the country (corresponding to the SE1 and SE2 price zones) whereas demand is concentrated in the south (corresponding to zones SE3 and SE4). This puts an additional burden on the grid, where greater distance between supply and demand leads to inevitable energy losses. Since R1&2 were located in a higher demand price zone (SE3) this meant that the aforementioned grid complications were less of an issue.

These results lead us to conclude that the shutdown of the Ringhals 1 & 2 reactors has had a negative impact on electricity prices: first by decoupling prices between zones of greater supply and zones of greater demand, second by putting greater burdens on the electrical grid that now has to compensate for greater distances between supply and demand and third by exposing high-demand zones to the generation unreliability of wind generation (when compared with nuclear generation) leading to supply uncertainty and therefore higher prices.

Policy Recommendations

Based on our results we can make the following recommendations to Swedish energy authorities:

- Make sure that the lifetime of plants Ringhals 3 and 4 is extended as much as possible, just like other plants have been granted extensions around the world.
- Avoid any further nuclear power plant shutdowns, as they provide a proven backstop to fluctuation in generation from weather-dependent renewable energy.
- Further developments in wind and solar generation should be accompanied by a proportional development of storage capacity, in order to smooth over generation fluctuations that lead to price swings.
- The amount of storage required must come from a thorough and realistic analysis of generation capacity, energy demand and grid capabilities.
- Avoid excess stress on interconnects between pricing zones either by maintaining generation geographically close to centers of demand (as Ringhals 1 & 2 are close to the high-demand urban centers in zone SE3) or by further investment on inter-zone power lines to return to the original state of generation balance between pricing zones.
- The installation of new electricity generation sources should not be done without a careful analysis of the grid and how this new generation will be integrated in it. Installing more solar and wind just because it seems cheap based on LCOE analysis will have unexpected consequences.

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