Changes in volatility spillover effects in electricity markets when adding interconnectors: Evidence from Denmark

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***Abstract*—This paper examines how the expansion of cross-border transmission capacity affects volatility spillover patterns in the Danish electricity market. We specifically analyze the impact of two infrastructure projects: the Cobra Cable to the Netherlands (commissioned 2019) and the Viking Link to Great Britain (commissioned 2024). Denmark represents a particularly interesting case study due to its role as a bridge between Nordic hydropower-dominated electricity systems and continental European markets predominantly powered by thermal and renewable electricity supply. Using daily electricity prices from 2015 to 2024, we employ the Diebold and Yilmaz (2012) connectedness methodology to measure the magnitude and direction of volatility spillovers between Denmark's two price areas (DK1 and DK2) and their neighbouring markets. The methodological framework utilizes a VAR-based forecast error variance decomposition approach with rolling windows to capture the temporal variations of these relationships. This enables us to identify structural changes in market integration patterns coinciding with the commissioning of new transmission interconnectors. The ability to quantify price effects of fundamental changes to energy systems is crucial both for policy makers and market participants to make sound economic decisions in dynamic market conditions.**

***Index Terms*—connectedness, electricity interconnectors, electricity markets, volatility spillover**

I. Introduction

In this paper, we calculate the volatility spillover effects in the electricity market from Denmark to Sweden, Norway, Germany, the Netherlands, and the United Kingdom. Using the connectedness approach introduced by [1], we examine these spillover effects between Denmark and neighboring countries, paying particular attention to the introduction of electricity transmission cables among the aforementioned countries.

Since the introduction of the Third Energy Package in the European Union in 2008 ([2]), there has been a clear aim to achieve closer integration of Europe's energy markets. The rationale behind this goal is to boost efficiency in European energy markets and facilitate the introduction of intermittent renewable energy supply (RES). Larger, more integrated markets not only strengthen security of supply in a system increasingly reliant on unregulated generation, but also enhance economic efficiency through economies of scale. In practice, this closer integration has primarily been pursued by expanding the network of international (and domestic) electricity interconnectors among European countries. Although the electricity grids, particularly in Northern Europe, are now more closely linked, Europe is still some way from having a single electricity price.

The energy transition is not proceeding without friction and conflict. Exacerbated by the shortage of Russian natural gas, European consumers have faced unprecedented natural gas and electricity prices since autumn 2021. Although international agreements of electricity exchange proved robust (see [3]), the resulting energy crisis has led to serious political repercussions, with numerous instances of voter backlash against incumbent governments across Europe ([4]). In light of this, it is essential that decision-makers, as they advance the energy transition, take evidence-based decisions regarding the design of the European energy markets to prevent adverse, unforeseen consequences.

In this context, Denmark stands out as a prime example of a country that has both replaced fossil-fuel-based electricity generation (primarily coal-fired power plants) with renewable energy sources (mainly onshore and offshore wind power) and introduced new international electricity interconnectors over the past decade. Since 2010, Denmark has nearly doubled its installed wind power generation capacity from 3,800 MW to 7,200 MW by 2023 (equivalent to an increase from 21 TWh to 50 TWh). During the same period, coal-fired electricity production declined from 45.5 TWh per year to 8 TWh per year (2023).

As we proceed, we will analyze the effects of Danish design decisions using the connectedness approach. The idea is to apply the methodology introduced by [1] to determine whether it yields the expected results when fundamental changes occur in the electricity markets. Originally developed for financial market spillover analysis, this connectedness approach is increasingly employed in energy market research to capture interdependencies across different price areas. The measures

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we use reflect both total integration and bilateral interaction among the price areas included in the analysis. We expect the total integration measure to rise over time, driven by increasing interconnectedness among these areas. In addition, we anticipate that the *bilateral* connectedness between Denmark and the Netherlands/UK will grow relative to that between Denmark and Norway/Sweden, given the expansions in transmission capacities between Denmark and the Netherlands/UK.

While there currently exists a zoo of different analysis for volatility spillovers of combinations of energy commodities and price areas in the European energy markets (see for instance [5], [6], [7], [8], [9], [10], [11], [12], [13], [14]), this paper aims to investigate volatility spillovers with the potential of modeling future price distributions as a consequence of fundamental changes in the electricity markets. The difference is subtle, but important. While volatility spillover effects are interesting in themselves, they may also be considered building blocks in predicting future changes to prices once we introduce fundamental changes to the price areas in question.

With this in mind, we expect to observe two effects: i) the total connectedness index (TCI) to increase significantly, and ii) the pairwise connectedness index (PCI) between Denmark and UK, EU and Norway to increase significantly, while the PCI between Denmark and Sweden should remain unchanged (or decrease over time) due to no extension of infrastructure among those two countries.

If confirmed then this methodology is well equipped to model the effects of future price changes in electricity systems. Although it is beyond the scope of this paper, this approach is a straightforward and valuable tool for estimating how fundamental alterations in market design might influence electricity price levels across different price areas.

Of course, both the total and bilateral (pairwise) connectedness measures may also be influenced by other fundamental changes in the market that affect interactions among regions not involving Denmark. For instance, Norway's price area 2 increased its exchange capacity with the UK and Germany in 2020 and 2021, which most likely altered the interplay between Southern Norway and the UK/Germany. Between 2021 and 2023 the European energy markets were in crisis due to the abrupt shortfall of Russian natural gas as a consequence of the invasion of Ukraine. These factors make it difficult to isolate the effects of electricity transmission cables in the system, and this analysis should be considered a stepping stone in an exploratory analysis.

II. Data

An overview of the physical connectedness of the electricity system in Northern Europe is shown in Table I.

Our dataset entails daily electricity spot prices from the day-ahead markets of Denmark (DK), Germany (GER), the Netherlands (NL), the United Kingdom (UK), Norway's price area 2 (NO2), and southern Sweden (SE3 and SE4). The time period under consideration spans from 01/01–2015 to 31/01–2025. The regions have been selected based on their historical and evolving interconnections with Denmark. The analysis covers a sufficiently long time period to capture the impact of key infrastructure developments, including the expansion of electricity transmission cables between Denmark and the Netherlands/UK, as well as between Norway and the UK/Germany.

TABLE I
System interconnector specifications

Interconnector	Capacity	Commissioned
DK-GER	3500 MW	whole period
DK-NL	700 MW	09/2019
DK-UK	800 MW*	12/2023
NL-UK	1000 MW	whole period
NO2-UK	1400 MW	10/2021
NO2-GER	1400 MW	12/2020
NO2-DK	1700 MW	whole period
SE-GER	600 MW	whole period

* The capacity is expected to increase to 1400 MW in 2025.

Due to high correlation coefficients (¿0.95) between the price areas DK1 and DK2, SE3 and SE4, and NL and GER, the prices from these areas have been aggregated into DK, SE, and EU, respectively, using a simple average. This yields five aggregated price series in total: DK, EU, NO2, SE, and UK.

TABLE II
Descriptive Statistics.

	Mean	SD	Min	Max	ADF-stat.
DK	59.0	64.4	-57.9	501.5	-6.30*
EU	72.0	78.4	-53.9	699.4	-4.99*
NO	58.3	69.6	-3.5	660.1	-4.89*
SE	47.0	50.3	-8.31	485.8	-6.97*
UK	96.3	71.0	-57.8	773.3	-4.74*

The last column displays the augmented Dickey-Fuller (ADF) test statistic; * indicates that the time series is stationary.

III. Methodology

We employ a generalized vector autoregression (VAR) framework to analyze volatility spillovers. The methodology is based on a forecast error variance decomposition (FEVD), which measures how much of the variance in a given region's electricity price forecast error is attributable to shocks originating in other regions.[1] Given an N-variable $VAR(p)$ model:

$$x_t = \sum_{i=1}^{p} \Phi_i x_{t-i} + \epsilon_t, \quad \epsilon_t \sim \mathcal{N}(0, \Sigma), \tag{1}$$

we define the generalized spillover measures as follows:

- **Total connectedness index (TCI):**

$$S_g(H) = \frac{\sum_{i,j=1, i\neq j}^{N} \tilde{\theta}_{ij}^{g}(H)}{N} \times 100, \tag{2}$$

which captures the fraction of forecast error variances explained by spillovers from other variables.

[1] A key advantage of the generalized VAR approach is that it ensures variance decompositions remain invariant to the ordering of variables, addressing a common limitation of Cholesky factorization-based approaches.

- **Pairwise connectedness index (PCI):**

$$S_{ij}^{g}(H) = \left(\tilde{\theta}_{ji}^{g}(H) - \tilde{\theta}_{ij}^{g}(H)\right) \times \frac{100}{N}, \quad (3)$$

  which measures the net directional connectedness from market i to market j.

To capture the time-varying nature of spillovers, we employ a rolling-window estimation. This involves re-estimating the VAR-model using a fixed window size of 650 days that moves forward in increments of one day. Rolling estimations provide a dynamic perspective on how spillovers evolve over the sample period. The window size of 650 data points was chosen as it was the smallest subset that provided valid results during estimation.

IV. Results

A. Total connectedness index (TCI)

Figure 1 displays the total connectedness index from 2015 to 2025. A general upward trend is clearly visible, with significant increases particularly in the latter third of the period. Both linear and polynomial trend tests (see Table III) suggest a statistically significant rise in system-wide spillovers over time. This aligns with the expectation that new interconnectors, such as the Cobra Link (2019) and Viking Link (2024), in addition to NorLink and North Sea Link, enhance cross-border electricity trading and thus integrate regional markets more closely. The TCI measure inherently captures all system-wide spillovers, indicating that closer market coupling in any part of the network can raise overall spillover effects. The TCI has nearly doubled throughout the time period. This result is consistent with the significant increase in transmission capacity between the price areas since 2015.

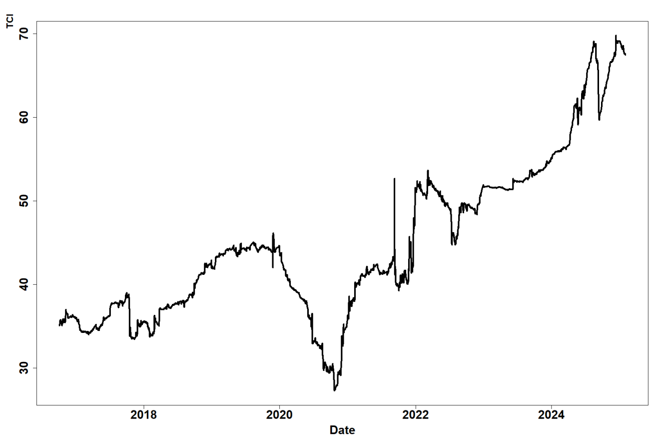

Fig. 1. Rolling total connectedness Index (TCI) among Denmark, EU, Southern Norway (NO2), the UK, and Southern Sweden (SE). TCI is displayed in the y-axis, the time-scale is displayed on the x-axis.

B. Pairwise connectedness indices (PCI)

Figure 2 provides the pairwise connectedness indices between Denmark (DK) and the four other aggregated areas (EU, NO, SE, and UK). As with the TCI, these bilateral indices generally exhibit upward trends. However, the magnitude and timing of changes vary. For instance, the DK–NO pair shows one of the stronger trends, possibly reflecting Norway's expanded interconnectors, whereas the DK–EU trend appears more modest. Initially we expected larger increase in the pairwise connectedness index between Denmark and the EU than our results indicate.

Table III summarizes the main trend statistics for both TCI and PCI (linear and quadratic). Most pairs, as well as the total index, show a statistically significant upward movement over the sample period. The trend analysis for Denmark shows almost no trend in the PCI between Denmark and Sweden, while the trend components in the PCI between Denmark and the other price areas are much stronger.

This is also confirmed by the graphs in Figure 2. The PCI between Denmark and Sweden is constant or falling, while the PCI between Dnemark and the other areas is consistently higher toward the end of the time period.

TABLE III
Trend analysis results for rolling TCI and PCI

Pair	Model	Intercept	Linear Term	Quadratic Term	R^2
TCI	Linear	31.1	9×10^{-3}	—	0.70
	Quadratic	38.4	-5.3×10^{-3}	4.7×10^{-6}	0.82
DK–SE	Linear	71.7	-3.3×10^{-3}	—	0.07
	Quadratic	66.6	6.7×10^{-3}	-3.3×10^{-6}	0.11
DK–UK	Linear	-6.4	2.1×10^{-2}	—	0.68
	Quadratic	16.8	-2.5×10^{-2}	1.5×10^{-5}	0.90
DK–NO	Linear	11.1	7.8×10^{-3}	—	0.18
	Quadratic	34.8	-3.9×10^{-2}	1.5×10^{-5}	0.59
DK–EU	Linear	3.5	8.0×10^{-3}	—	0.52
	Quadratic	9.0	-2.6×10^{-3}	3.6×10^{-6}	0.58

All estimates are statistically significant at the 99% confidence level.

From a market-design perspective, these results suggest that Denmark is becoming increasingly synchronized with its neighbors as the interconnectivity increases. Nonetheless, the degree of synchronization appears dependent on various external factors, including the expansion of interconnectors in other regions (such as Norway) and broader supply shocks like the European natural gas crisis.

V. Discussion and Conclusion

This paper analyzes how the expansion of cross-border electricity transmission capacity has influenced volatility spillover patterns in the Danish electricity market. By utilizing the connectedness framework [1] on daily price data from 2015 to early 2025, we identify two key results:

1) **Significant increase in the total connectedness index (TCI).** The TCI has nearly doubled over the sample period, indicating that Northern European price areas have become more integrated. This broader coupling reflects not only Danish interconnectors like the Cobra (2019) and Viking Link (2024) but also other large-scale links (e.g., Norway–Germany, Norway–UK).

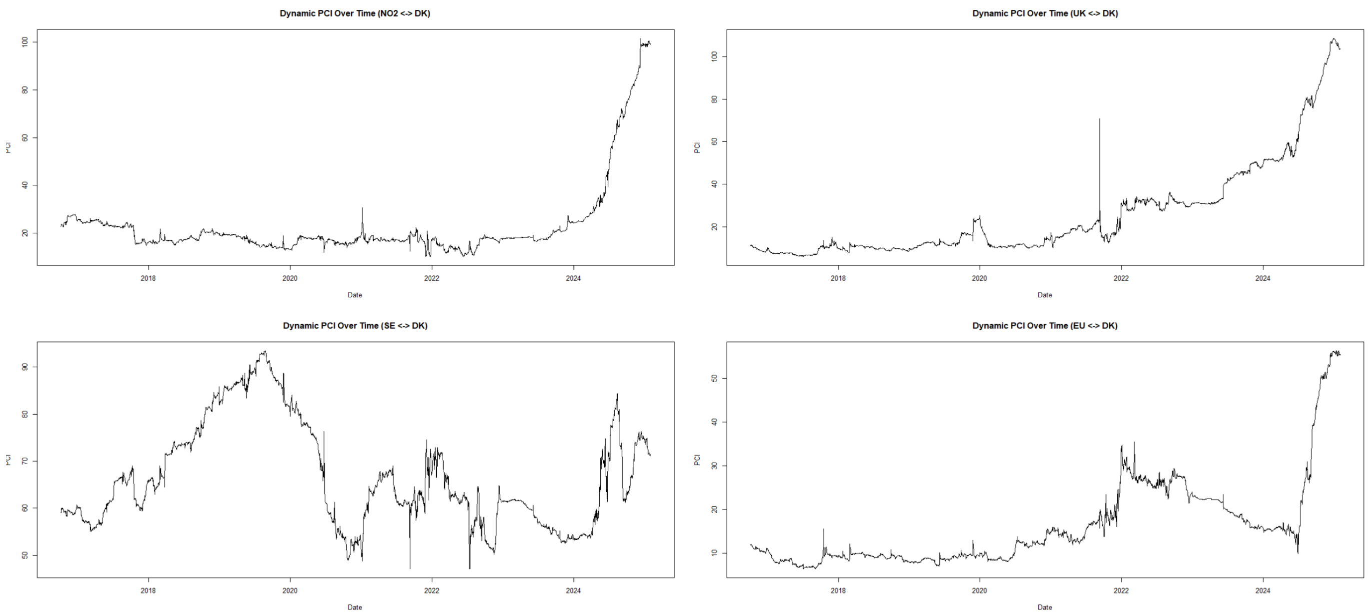

Fig. 2. In this figure we display the rolling pairwise connectedness indices in the system for the areas connected with Denmark. The system includes th pairwise connectedness measures between Denmark and the price areas (starting top left, moving clockwise) Southern Norway, UK, Southern Sweden and EU (Germany and Netherlands).

2) **Upward trends in Pairwise Connectedness (PCI) for key Danish counterparties.** The bilateral connectedness between Denmark and Norway, the UK, and the EU aggregate (Germany/Netherlands) rises more steeply than that between Denmark and Sweden (which is flat or falling). This pattern aligns with the fact that Denmark has expanded its exchange capacities primarily with continental Europe and the UK, whereas its capacity with Sweden remains largely unchanged.

These results confirm that the connectedness approach effectively captures how fundamental, physical changes in transmission infrastructure can shift price interdependencies over time. As such, the methodology can provide a valuable basis for projecting potential price effects when future structural changes occur (e.g., new cables, further market integration, or alterations in fuel mixes).

These findings align with the expectations that new physical interconnectors contribute to tighter market coupling and stronger volatility spillovers. However, the analysis also underscores that Denmark's market is only one part of a larger interconnected system. The introduction of other large-capacity cables (e.g., between Norway and Germany/UK), in addition to exogenous shocks such as the European energy crisis, also drives increased integration.

A. Policy implications and future research

A higher level of connectedness generally enhances market efficiency and facilitates renewable energy integration by allowing for more fluid cross-border electricity flows. At the same time, it also implies that localized price shocks can more readily propagate across multiple regions. Policy makers should therefore balance the benefits of expanded interconnection (e.g., improved security of supply, resource sharing) with the need for robust market design and risk management measures—especially in times of increased price volatility.

The evidence presented highlights the evolving nature of Denmark's electricity market within a broader Northern European context, showing that recent infrastructure expansions correlate with rising interconnectedness and volatility spillover effects. While this analysis does not enable us to conclude that observed volatility spillover estimates may alone explain or model price effects as a consequence of fundamental changes in market conditions, the results are still consistent with the tighter interconnection between price areas in Northern Europe. As such, the volatility spillover may be necessary although not sufficient to model future price variations between electricity price areas.

B. Suitability for modeling future changes

One objective of this paper was to investigate whether observed changes in spillover patterns match the fundamental expansions in cross-border capacity—thereby validating the use of connectedness measures to *predict* future price responses to structural shifts. Given that the TCI and PCI evolve consistently with known infrastructural developments (e.g., Cobra and Viking Links) and that the expected bilateral relationships (such as DK–EU and DK–UK) indeed show upward trends, the results suggest that:

- **Connectedness metrics can help forecast how new cables or capacity increases might redistribute price pressures** across multiple areas, particularly when cou-

pled with fundamentals like generation costs, demand patterns, or reservoir levels.
- **Spillover analysis can be integrated with scenario planning** to estimate potential price corridors under different infrastructure expansions or policy interventions (e.g., carbon pricing, capacity markets).

C. Directions for Future Research

Although these findings corroborate the idea that physical grid expansions spur cross-border spillovers, further analyses could strengthen the understanding of specific mechanisms. For example:

- **Fundamental market drivers:** Incorporating generation data (wind, hydro, solar) and consumption forecasts to separate purely physical capacity effects from broader supply-demand shocks.
- **Comparisons with GARCH-based or wavelet approaches:** Testing the robustness of these results using alternative modeling frameworks could provide additional insight into the frequency and duration of spillover effects.
- **Application of connectedness measures to fundamental market changes:** The most natural next step is validating connectedness measures as a way to model future price changes between connected price areas. If it is possible to model TCI and PCI measures with regard to future changes in fundamental conditions, it may also be possible to use these measures to estimate and create simulation scenarios of the price-change-effects of future fundamental changes to the electricity system.

In conclusion, the significant rise in both total and bilateral connectedness measures in the Danish electricity market points to a strong link between fundamental infrastructure developments and changing price dynamics. This outcome highlights the power of the connectedness methodology to detect shifts in inter-regional dependencies and underscores its potential utility for projecting how future capacity expansions or policy interventions might reshape electricity price landscapes.

References

[1] F. X. Diebold and K. Yilmaz, "Better to give than to receive: Predictive directional measurement of volatility spillovers," *International Journal of Forecasting*, vol. 28, no. 1, pp. 57–66, 2012.

[2] J. De Jong, "The 2007 energy package: The start of a new era?" In *European Energy Law Report V*, M. Roggekamp and U. Hammer, Eds. Intersentia, 2008, pp. 95–108.

[3] B. Sæther and A. Neumann, "The effect of the 2022 energy crisis on electricity markets ashore the north sea," *Energy Economics*, vol. 131, 2024.

[4] E. Voeten, "The energy transition and support for the radical right: Evidence from the netherlands," *Comparative Political Studies*, vol. 58, no. 2, 2024.

[5] L. Han, N. Kordzakhia, and S. Trück, "Volatility spillovers in australian electricity markets," *Energy Economics*, vol. 90, 2020.

[6] H. Chuliá, D. Furió, and J. M. Uribe, "Volatility spillovers in energy markets," *The Energy Journal*, vol. 40, no. 3, 2019.

[7] T. Pantos, S. Polyzos, A. Armenatzoglou, and I. Kampouris, "Volatility spillovers in electricity markets: Evidence from the united states," *International Journal of Energy Economics and Policy*, vol. 9, no. 4, pp. 131–143, 2019.

[8] B. Zhu, L. Huang, L. Yuan, S. Ye, and P. Wang, "Exploring the risk spillover effects between carbon market and electricity market: A bidimensional empirical mode decomposition based conditional value at risk approach," *International Review of Economics And Finance*, vol. 67, pp. 163–175, 2020.

[9] Y. Wang, S. Liu, M. Z. Abedin, and B. Lucey, "Volatility spillover and hedging strategies among chinese carbon, energy, and electricity markets," *Journal of International Financial Markets, Institutions and Money*, vol. 91, 2024.

[10] S. Zeng, J. Jia, B. Su, C. Jiang, and G. Zeng, "The volatility spillover effect of the european union (eu) carbon financial market," *Journal of Cleaner Production*, vol. 282, 2021.

[11] X. Gong, R. Shi, J. Xu, and B. Lin, "Analyzing spillover effects between carbon and fossil energy markets from a time-varying perspective," *Applied Energy*, vol. 285, 2021.

[12] W. Zhou, Q. Gu, and J. Chen, "From volatility spillover to risk spread: An empirical study focuses on renewable energy markets," *Renewable Energy*, vol. 180, pp. 329–342, 2021.

[13] J.-B. Geng, Y.-J. Du, Q. Ji, and D. Zhang, "Modeling return and volatility spillover networks of global new energy companies," *Renewable and Sustainable Energy Reviews*, vol. 135, 2021.

[14] C. Lyu, H. X. Do, R. Nepal, and T. Jamasb, "Volatility spillovers and carbon price in the nordic wholesale electricity markets," *Energy Economics*, vol. 134, p. 107 559, Jun. 2024. DOI: 10.1016/j.eneco.2024.107559.