Renewable energy sources and power price volatility - The role of power grid interconnections

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1st October 2025

1 Motivation and Research Question

This research aims to estimate the effect of intermittent renewable energy sources penetration, notably solar photovoltaic and wind power, on the wholesale electricity price volatility, taking into account grid flexibility through a recent, persistent and exogenous shock in the Estonian-Finland power interconnection.

Intermittent renewable energy sources (IRES hereafter) are one of the mainstream and available solutions adopted by many countries to try to decarbonise our economy. Estonia is no different. To respect political agreements and fight environmental damage, it has committed to achieve carbon neutrality in 2050, betting massively on wind and solar photovoltaic in its energy transition strategy. The 2024 Estonian TSO report highlights that electricity produced from IRES like solar and wind covered 39 per cent of the total production. The 694 megawatts of installed wind power resulted in 1164 gigawatt-hours of electricity. Compared to 2023, wind energy production increased by an impressive 70 per cent, highlighting the Estonian commitment. The same year, production from 1.2 gigawatts of installed solar photovoltaic (PV) power plants accounted for one gigawatt-hours. Renewables overall covered 39 per cent of the total consumption.

Estonian power sector presents an interesting case study. First, it heavily relies on imports to satisfy the demand for electricity. In 2024, almost half of its demand has been imported, especially from Latvia and Finland. In addition, Estonia is weakly connected to other major European grids, creating a more rigid and less stable power system. The connection with Finland is provided through two DC cables: Estlink-1 and Estlink-2 of about 350 and 650 megawatts of capacity respectively. The latter, relying on the estimation of the Russian links using actual cross-country flows from the European Network of Transmission System Operators for Electricity (ENTSO-E), corresponds to about 20 per cent of total Estonian transmission capacity. Given that the Scandinavian country is the major energy exchange partner of the Baltic one, it is comprehensible that a fault on this connection could have seriously undermined the stability of the Estonian power system, especially under heavy expansion of IRES.

Existing literature has been vast on the effect of IRES on the mean and dispersion of wholesale electricity prices. While the merit order effect (MOE hereafter) has been confirmed by the majority of studies, the conclusion on the effect on wholesale electricity price volatility (EPV henceforth) is mixed and depends on various factors like load level and grid flexibility. This motivates this study to dig deeper into this subject taking into account grid interconnections.

2 Literature Review and Contribution

As previously mentioned, existing literature has been exhaustive on the MOE, but less so on the effect of IRES on price volatility. The merit order effect states that RES decreases the wholesale electricity prices theoretically shifting the supply curve to the right, crowding out costly peak-load power plants. To conclude on these topics, the literature has mainly opted for two separate techniques. Authors like [Ciarreta et al., 2020], [Maniatis and Milonas, 2022] and [Kyritsis et al., 2017] followed the path of [Ketterer, 2014] using a time-series approach to test for MOE and variability clusters. More precisely, variants of the Generalised Autoregressive Conditional Heteroskedasticity (GARCH) model are applied using mostly hourly observation aggregated into daily dataset in the context of Spain, Greece, Germany and Denmark.

The second branch of the literature adopts a quantile regression model to answer the same research question. [Maciejowska, 2020] and [Tselika, 2022] applied this concept on German and Danish wholesale electricity prices. The latter focuses on using a panel structure and compares it with the time-series strategy. Claiming that a panel structure fits the nature of electricity price formation that is through bids that treat each hours independently. Finally, [Sapio, 2019] make use of a quantile regression and a new transmission line between Sardinia and the Italian peninsula, stressing the importance of grid flexibility.

This paper contributes to the literature with evidence from a Baltic country on the effect of IRES on price variability, applying [Tselika, 2022] panel structure on high resolution data. Special emphasis is given on the effect of grid flexibility along the line of [Sapio, 2019], which has been highlighted as a possible buffer of high price fluctuations.

3 Identification Strategy and Data

From 26th January to 13th September 2024, a short circuit has drastically undermined the connection between Finland and Estonia. Estlink-2 is non-operational, consequently the bilateral transmission capacity decreases from one gigawatt to 350 megawatts. It's crucial at this point to check whether the curtailment of solar and wind power has not occurred, otherwise the exogeneity of these two sources will be lost. Data from the Estonian statistical office inform that solar and wind production were higher for every month in 2024 than in 2023. In addition, giving the net-importer nature, it seems unlikely to shut down some production. Regressing the actual wind and solar production on the solar irradiation and wind speed and a fault dummy, the cable effect is non significant, excluding IRES curtailment.

$$Q_P(\tau) = (\alpha_i + \delta_i q(\tau)) + \beta_1^\tau S_{it} + \beta_2^\tau W_{it} + \beta_3^\tau L_{it} + \beta_4^\tau C_{it} + \beta_5^\tau Z_{it} + \beta_6^\tau X_{it} + e_{it}^\tau, \tau \in [0, 1] \tag{1}$$

The econometric specification follows Equation 1. The subscript "i" refers to the cross-sectional dimension, hence the 24 hours and "t" to the time dimension, days in this case. The dependent variable is $Q_P(\tau)$ and represents the τ-th quantile of the wholesale day-ahead electricity prices in EUR/MWh (megawatt-hours). Note that the τ superscript indicates that the estimated coefficients vary across quantiles. The independent variables are the forecasted wind and solar sources production in megawatts, noted with W_{it} and S_{it} in the equation. A cable fault is introduced with a binary variable C_{it}, being one is the cable is operational. Load in megawatts is an important component, denoted by L_{it}. Finally, weekends, national holidays and seasonal variation are taken into account with a set of binary indicators Z_{it}. Lagged day-ahead price variable could be added to account for short-term seasonal pattern if seasonality tests suggest to. Control variables like fuel prices could help in the robustness check phase through the variable X_{it}. Further variations in the empirical strategy could include the usage of cable-IRES interaction terms or the use of IRES penetration (IRES/Load).

Standard errors are calculated using bootstrap technique and clustered. To ensure the stationarity of the variables, Augmented Dickey-Fuller (ADF) unit root test is carried out. Thanks to panel structure, unit fixed effects could be implemented. This is particularly useful to control for unobserved heterogeneity across each individual hour of the day. For example night and day time. The term $(\alpha_i + \delta_i q(\tau))$ captures hourly time-invariant variation through α_i and δ_i captures the quantile-specific unit fixed effects.

Estonian wholesale day-ahead electricity price, forecasted wind and solar production, forecasted load, forecasted scheduled cross-border flows and Estonian solar irradiation and wind speed are available in hourly format from ENTSO-E and Estonia Environment Agency respectively. The data will be collected from January 2023 to November 2024, resulting in 16800 hours in total, so 700 days. In February 2025 the Baltic regions decoupled from Russian grid, leaving BRELL grid interconnection, which introduced a structural brake. In addition, towards the end of December 2024 a second fault on the same connection happened. Due to these events, the data will be considered until November 2024. Year 2022 is preferably excluded due to the war in Ukraine.

4 Time Line

- **10th October** Sharpening research question and empirical strategy
- **October - early November** Estimate the model, get first results and finalise literature review
- **November** Extend the model, complete the thesis
- **End of November** Submission first draft
- **15 December** Final version
- **2nd week of January** Defence period

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