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# Disentangling the electricity supply curve: the role of green and brown energy sources

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## Abstract

This paper<sup>1</sup> investigates the determinants of wholesale electricity and EU ETS allowance prices in the euro area from February 2010 to December 2025 using a nonparametrically estimated time-varying coefficient VARX model with stochastic volatility. This framework allows for gradual changes in electricity market shock transmission, particularly those associated with the increasing importance of electricity generation from green energy sources. We develop a partial equilibrium model to motivate an identification strategy that disentangles the electricity supply curve by energy source and incorporates endogenous responses of emission allowance price. Our historical shock decomposition indicates that the post-pandemic surge in wholesale electricity price was driven mainly by demand recovery and positive emission allowance market shocks, consistent with regulatory tightening and other developments in the emission allowance market. By contrast, adverse brown supply shocks played a limited and transitory role following Russia's invasion of Ukraine. A counterfactual with a fixed carbon tax suggests that this muted effect partly reflects the buffering role of the EU ETS.

**Keywords:** Wholesale electricity prices; Green energy; Emission allowances; Time-varying VAR; EU ETS; Energy shocks.

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# Introduction

Since the pandemic, energy markets have been repeatedly affected by geopolitical supply-side shocks, most notably the Russian invasion of Ukraine and the escalation of conflict in the Middle East, including the war in Iran. These developments have exposed the vulnerability of electricity markets to external disturbances and brought them to the forefront of policy discussions. Price volatility has been particularly pronounced: at its peak in August 2022, the price of German baseload power for year-ahead delivery exceeded 450 EUR/MWh, representing a more than fivefold increase year-on-year (Wilson, 2022).

The European electricity market is shaped by a complex interplay of supply and demand factors. On the supply side, the electricity production is influenced by the increasing share of green energy sources (e.g., wind, solar, hydropower), supported by the “Fit for 55” policy, which aims to halve carbon emissions relative to 1990 levels by 2030 (European Council, 2025), climate policies, and availability of brown energy sources (e.g., coal, oil, natural gas). Simultaneously, the state of the business cycle shapes the electricity demand.

In this paper, we examine the key drivers of wholesale electricity prices in the post-pandemic period. First, we propose a simplified yet realistic partial equilibrium model to provide a theoretical framework that links wholesale electricity prices to green and brown energy sources, emission allowances, and electricity demand. The model incorporates the “colour” of energy sources and utilises the merit order ranking of electricity production to decompose the electricity supply curve and identify structural shocks originating from green and brown energy sources, as well as those related to demand and emission allowance market innovations.

Second, we apply our theoretical framework empirically, by using a time-varying structural VARX model with stochastic volatility identified with theoretically motivated sign restrictions. The time-varying specification is intended to capture gradual, but structurally important, evolution in the transmission of shocks, including changes associated with the growing share of electricity generation from green energy sources. Our semi-parametric approach allows, but does not require, every response to vary over time.

Our analysis yields five main policy conclusions. First, we show that the source of energy supply shocks matters and its effects change over the sample period. In other words, the response of wholesale electricity and emission allowance prices varies depending on whether the shock originates from green or brown energy source. While prior literature has demonstrated shock dependence in oil markets (e.g., Baumeister and Hamilton, 2019; Kilian, 2009; Boer et al., 2023) and in exchange rate pass-through (e.g., Comunale and Kunovac, 2017; Forbes et al., 2017), our findings extend this insight to wholesale electricity and carbon markets.

Second, we show that the sensitivity of wholesale electricity prices to green supply shocks has increased over time, which reflects the growing share of electricity production from green energy sources. Given the inherently stochastic and weather-dependent nature of electricity production from green energy sources, this finding underlines the importance of technological advances in energy storage to reduce reliance on fossil fuels and ensure production stability as the energy transition progresses.

Third, we find that demand recovery and the tightening of climate policy were the key drivers of the post-pandemic increase in wholesale electricity prices. This contributes to the literature on the determinants of the wholesale electricity and emission allowance prices (e.g., Boersen and Scholtens, 2014; Chung et al., 2018; Ganepola et al., 2023).

Fourth, our analysis indicates that emission allowances not only incentivise emissions reductions (Colmer et al., 2025; Dechezleprêtre et al., 2023) but also acted as a stabilising mechanism in response to brown energy supply shocks. This buffering function became more apparent after the Russian invasion of Ukraine. Our counterfactual analysis suggests that replacing the EU Emissions Trading System (EU ETS) with a flat carbon tax would have led to substantially larger wholesale electricity price increases during the 2022 energy crisis. We attribute this to the market-based nature of the ETS: reduced output from brown energy sources lowers demand for emission allowances, which in turn decreases their market price. This mitigates the marginal cost of electricity production and ultimately moderates wholesale electricity price increases after brown supply shocks.

Finally, we develop a novel partial equilibrium model of the electricity market that incorporates emission allowances and distinguishes between green and brown energy sources. In doing so, we contribute to the literature on electricity market structure (e.g., Eriksson et al., 2019; Hannesson, 2025; Hirth, 2013).

The remainder of the paper is structured as follows: Section 1 provides a brief review of the relevant literature. In Section 2, we introduce a straightforward theoretical model that connects electricity and emission allowance markets and serves as a baseline for our identification strategy. Section 3 details the data, econometric methodology, and the structural identification of the shocks. Section 4 presents the results and discusses policy implications. Finally, Section 5 concludes the paper.

## 1 Literature review

Energy price developments are important for economic activity, with much of the existing literature focusing on oil-related shocks (e.g., Baumeister and Peersman, 2013; Blanchard and Gali, 2007; Jiménez-Rodríguez and Sanchez, 2005; Huntington and Liddle, 2022; Kilian, 2008, 2009, 2014). In comparison, electricity markets have received less attention. Ganepola et al. (2023) analyse the effects of both supply- and demand-side shocks on UK wholesale electricity prices. Their results highlight the growing importance of natural gas and demand shocks in driving post-pandemic electricity price increases, as well as a short-run negative impact of electricity-specific shocks on electricity output.

Electricity price fluctuations also have broader economic consequences. Higher electricity prices contract economic activity (He et al., 2010), and increase inflation (Lim and Yoo, 2013). Yin et al. (2019) study electricity market liberalisation in China and conclude that a limited-competition model provides greater social welfare than full liberalisation. In the Chilean case, Agurto et al. (2021) show that without the investment in renewable energy sources, the delays in the construction of new power plants would

decrease the gross domestic product growth through higher electricity prices. Gedikkaya et al. (2020) show that the pass-through of electricity price shocks into final prices is in Turkey largest for sectors with high electricity dependency.

These aggregate effects also have an affordability and just-transition dimension. Wholesale electricity and emission allowance price shocks need not pass through one-for-one to retail tariffs, yet households differ markedly in energy expenditure shares, housing efficiency, heating technologies and their ability to adjust consumption. Känzig (2023) finds that restrictive carbon policy shocks raise energy prices and reduce activity, with poorer households bearing larger consumption losses. For the EU, Koukourikis et al. (2024) document persistent and heterogeneous energy poverty exposure across countries, regions and socioeconomic groups. Carbon pricing design and revenue recycling therefore matter for both distributional outcomes and the political durability of the transition.

A distinctive feature of electricity, unlike other commodities, is that storage is still technologically cumbersome. In the European Union (EU), wholesale electricity prices are determined according to the merit-order system, in which electricity producers are dispatched in ascending order of marginal cost. As a result, the spot price is set by the highest cost of a producer that is still required to meet demand. The marginal cost of electricity is primarily determined by three factors: fuel input costs, emission allowances, and operational costs. Green energy sources have the lowest marginal costs, due to negligible fuel and emissions costs, and therefore appear early on the supply curve.<sup>2</sup> In contrast, brown energy-based electricity producers face higher marginal costs due to reliance on fuel market prices (e.g., coal or natural gas) and the cost of emission allowances (Gasparella et al., 2023).

The second strand of the literature concerns merit-order mechanism, which implies a convex electricity supply curve (Kirschen, 2003). Because electricity demand is inelastic in the short term, market prices of electricity are mainly driven by supply-side factors. An increase in the share of electricity produced from green energy sources shifts the supply curve rightward, exerting downward pressure on prices. Hirth (2018) finds that increased electricity production from green energy sources in Germany and Sweden between 2008 and 2015 lowered wholesale electricity prices. Liebensteiner et al. (2025), however, show that higher gas and CO<sub>2</sub> allowance prices and stronger demand can counteract this merit-order effect. Fossil fuel-based producers can therefore remain marginal price setters even as electricity production from green energy sources expands, particularly when storage and other sources of flexibility are limited (Gasparella et al., 2023). Our partial equilibrium model incorporates this by assuming that the marginal bid (i.e., the last accepted bid that determines the market price of electricity) is always provided by a brown energy-based electricity producer.

To incentivise reduction of greenhouse gas (GHG) emissions, governments typically implement carbon taxes or emissions trading systems (Green, 2021). The EU adopted the latter and in 2005 launched the EU ETS, which became EU's key climate policy instrument. EU ETS functions as a cap-and-trade scheme. Each year, a binding cap is placed on total amount of allowed emissions for covered sectors. Emission allowances are either auctioned or allocated for free, and firms may trade them. Non-compliance results in financial penalties and a requirement to make up the shortfall in the following

<sup>2</sup> Note, investment costs associated with green energy-based power plants are not included in the calculation of marginal costs.

year (European Commission, 2026). Most auction revenues are returned to EU member states, who use them to support climate-related, renewable energy, and energy-efficiency projects (European Commission, 2023).

The third strand of the literature studies EU ETS allowance price formation and the interaction between the carbon and electricity markets. The EU ETS promotes decarbonisation through incentives to adopt cleaner technologies and through a declining cap on emissions. Its institutional design has also evolved substantially. The Market Stability Reserve began operating in 2019 to address the historical allowance surplus, while the 2018 reform introduced allowance cancellations and helped restore confidence in the system. Perino et al. (2021) describe these reforms and stress that a quantity-based reserve can have complex stability and investment effects. The EU ETS covers roughly 10,000 installations across the energy and manufacturing sectors, along with aviation and maritime transport (European Commission, 2026).

Effective decarbonisation requires close monitoring of both allowance supply and market prices. If prices are too low or supply of allowances is too high, firms may lack incentives to reduce emissions. Conversely, excessively high prices or rapid cap reductions could incentivise carbon leakage<sup>3</sup> and reduce competitiveness of regulated firms. Several supply-side factors reduce the market price of emission allowances, including the expansion of renewable energy (Koch et al., 2014) and changes in fuel use for electricity production in response to input price differences<sup>4</sup> (Boersen and Scholtens, 2014).

EU ETS allowance prices are also influenced by demand and financial market conditions. Extreme temperatures can raise allowance prices through electricity demand for heating and cooling (Mansanet-Bataller et al., 2007), while expectations about economic activity explain a substantial share of EU ETS allowance price variation (Koch et al., 2014). When fossil fuel generators set the marginal bid,<sup>5</sup> positive demand shocks in the electricity market tend to increase emission allowance prices. This occurs because the additional demand must be met by carbon-intensive electricity producers, given that electricity production from green energy sources is already fully utilised earlier in the merit-order dispatch due to their lower marginal costs (Gasparella et al., 2023). Empirical evidence suggests that the EU ETS has contributed to reductions in greenhouse gas emissions without adversely affecting employment or public revenue (Colmer et al., 2025; Dechezleprêtre et al., 2023). Ampudia et al. (2022) find only a limited role for speculative financial activity in explaining the rise in EU ETS allowance prices observed in 2021. Känzig (2023) uses high-frequency movements around regulatory announcements to identify a narrower carbon policy shock. By contrast, the emission allowance market shock identified in this paper combines regulatory supply news, compliance demand and financial market forces.

These strands of the literature leave an empirical gap. Existing work decomposes electricity prices (Ganepola et al., 2023; Hirth, 2018), studies links between electricity and allowance prices (Boersen and Scholtens, 2014; Chung et al., 2018), or models the value of variable renewable generation (Eriksson et al., 2019), but does not jointly combine source-specific electricity supply, endogenous allowance-price feedback and

<sup>3</sup> Carbon leakage refers to a situation in which high-emitting firms relocate their production processes to countries with laxer carbon policies (European Commission, 2026)

<sup>4</sup> The switching effect describes the substitution between different energy sources with varying emission intensities due to their price difference. For example, if the marginal production costs of coal-based electricity production exceed those of gas-based electricity production, gas-based electricity will be supplied to the market first, and vice versa (Boersen and Scholtens, 2014).

<sup>5</sup> Fossil fuel-based electricity producers accounted for 86% of price-setting in 2022 despite generating 34% of electricity (Gasparella et al., 2023).

time-varying transmission. We fill this gap with a theory-consistent identification of demand, green and adverse brown supply, and allowance market shocks, together with a counterfactual comparison of the EU ETS and a fixed carbon tax.

## 2 Theoretical framework

In this section, we present a theoretical model that incorporates the impact of emission allowances and the “colour” of electricity production to explain the formation of demand and supply in the electricity market. We extend the partial equilibrium model of the electricity market proposed by Eriksson et al. (2019) by introducing the role of emission allowances. We use this model to motivate the propagation mechanisms of structural shocks, which we examine empirically in this paper.

### 2.1 Electricity demand

In our framework, the economy is populated by many individuals<sup>6</sup> ( $i$ ) who consume electricity ( $E$ ) and other goods ( $Y$ ). Each consumer maximises their utility, which has a quasi-linear functional form:

$$U_i(E_i, Y_i) = \theta_i \left( \frac{E_i^{1-\frac{1}{\alpha}}}{1-\frac{1}{\alpha}} \right) + \mu_i Y_i,$$

where  $\theta_i$  and  $\mu_i$  denote individual specific preferences for electricity and other goods, respectively. The parameter  $\alpha > 0$  is related to the substitution between electricity and other goods. Individuals face the following budget constraint:

$$p_E E_i + p_Y Y_i = I_i,$$

where  $p_E$  and  $p_Y$ , denote the market price of electricity and other goods (for simplicity normalised to  $p_Y = 1$ ). Optimal consumption bundle is obtained by solving the following standard utility maximisation problem, subject to budget constraint:

$$\max_{E,Y} \theta_i \left( \frac{E_i^{1-\frac{1}{\alpha}}}{1-\frac{1}{\alpha}} \right) + \mu_i Y_i \text{ s.t. } p_E E_i + Y_i = I_i.$$

The solution to this problem yields the following electricity demand function for individual  $i$ :

$$E_i = \left( \frac{\theta_i / \mu_i}{p_E} \right)^\alpha.$$

Aggregating across all individuals gives the market demand for electricity:

$$D_E = p_E^{-\alpha} \sum_{i=1}^I \left( \frac{\theta_i}{\mu_i} \right)^\alpha$$

<sup>6</sup> Total demand for electricity can be extended to firms within the same framework. Notice that equation 1 can represent the production function that is later conditioned to the costs of other inputs. However, in this section we continue to use consumer problem as the reference for simplicity and sharper distinction from producers of electricity.

This formulation mirrors that of Eriksson et al. (2019) and is included here for completeness. As expected, the demand for electricity is inversely related to its price and positively to the ratio between the marginal utility of consuming electricity and other goods.

## 2.2 Electricity supply

In contrast to Eriksson et al. (2019), we distinguish two stylised electricity production types, based on the underlying energy source: green ( $S_G$ ) and brown ( $S_B$ ).<sup>7</sup> Green denotes renewable generation with low marginal cost and near-zero direct operating emissions, including hydropower, solar and wind. Brown denotes the emissions-intensive marginal technology, represented by coal, natural gas and oil. These are theoretical labels. The empirical residual/non-renewable category defined in Section 3.2 is broader because it also contains nuclear power. By definition, the total electricity supply can be calculated as:

$$S_E = S_G + S_B.$$

The electricity supply curve is structured according to the "merit order" principle, ranking producers by their marginal production costs. Consequently, the market price of electricity aligns with the marginal cost of the highest-cost producer, i.e. the marginal bid. Under this approach, the initial segment of supply curve is provided by producers that utilise green energy sources, which typically have negligible marginal production costs compared to brown energy sources like coal and natural gas. For analytical simplicity, we assume that the marginal production cost of electricity from green energy sources is zero. The output of green electricity producers is given by:

$$S_G = \phi_G f(\overline{K}_G),$$

where  $\overline{K}_G$  denotes the total installed capacity for electricity production from green energy sources, which increases with investments in green electricity production capacities. The capacity utilisation factor  $\phi_G \in [0, 1]$  is stochastic and varies primarily due to exogenous weather conditions.

We further assume that the electricity producer with highest marginal costs, which determines the market price of electricity, always produces electricity from brown energy sources. This assumption aligns with empirical evidence, as brown energy sources continue to act as the dominant price setters in the EU electricity market and are expected to retain this role at least until 2030, despite the gradual phase-out of fossil fuels and the ongoing expansion of production capacity based on green energy sources (Gasparella et al., 2023). Electricity production from brown energy sources corresponds to the residual load (i.e., the portion of electricity demand not met by electricity produced from green energy sources) and hence depends directly on the output from green energy sources. Formally, the supply of brown electricity is assumed to be always positive and is given by:

$$S_B = S_E - \phi_G f(\overline{K}_G)$$

The production function for brown electricity producers is:

$$S_B = AL^\beta,$$

<sup>7</sup> Eriksson et al. (2019) studied the equilibrium price of electricity and differentiated between variable renewable electricity sources and dispatchable supply.

where  $A$  stands for a productivity factor,  $L$  is the energy source used in production (e.g., coal, gas, or oil) and  $\beta < 1$  ensures decreasing returns to scale and increasing marginal production costs.

Brown electricity production generates GHG emissions, which must be compensated for by the purchase of emission allowances. To examine their impact on wholesale electricity prices, we incorporate the emission allowance market into our theoretical model. In this framework, the demand for emission allowances ( $Q_{ETS}^D$ ) is linked to the amount of electricity produced from brown energy sources:

$$Q_{ETS}^D = \lambda_{ETS} L,$$

where  $\lambda_{ETS}$  represents a fixed<sup>8</sup> emission intensity parameter that quantifies the GHG emissions generated per unit of brown energy input. Given:

$$L = \left(\frac{S_B}{A}\right)^{1/\beta},$$

we can rewrite the demand for emission allowances as:

$$Q_{ETS}^D = \lambda_{ETS} \left(\frac{S_B}{A}\right)^{1/\beta}$$

Hence, the demand for emission allowances is increasing with the quantity of electricity produced from brown energy sources ( $S_B$ ) and decreasing with the technological improvements ( $A$ ), that enhance efficiency of electricity production. Conversely, the supply of emission allowances,  $Q_{ETS}^S$ , is determined exogenously by the policymaker.

The representative brown electricity producer maximises profits, by considering both fuel costs and the cost of emission allowances. The profit function is given by:

$$\Pi_B = p_E A L^\beta - p_L L - p_{ETS} \lambda_{ETS} L,$$

where  $p_E$ ,  $p_L$ , and  $p_{ETS}$  denote the market price of electricity, brown energy source, and emission allowance, respectively. Solving this maximisation problem yields:

$$p_E = \frac{p_L + p_{ETS} \lambda_{ETS}}{\beta A L^{\beta-1}}.$$

This expression indicates that the market price of electricity,  $p_E$ , is positively related to the market price of brown energy source and emission allowances.

### 2.3 Structural shocks

Figure 1 provides a simplified graphical representation of the electricity and emission allowance markets. Figure 1 (left) illustrates the electricity market, with  $D_E$  representing electricity demand curve. The electricity supply curve is divided into two segments: green electricity producers ( $S_G$ ) supply the initial portion of demand, while brown electricity producers ( $S_B$ ) meet the residual load. The shape of the supply curve reflects the assumed zero marginal costs of green producers and increasing marginal costs for brown producers. Figure 1 (right) illustrates the emission allowance market. The supply of emission allowances ( $S_{ETS}$ ) is fixed in the short run. Hence, endogenous price fluctuations are primarily driven by shifts in emission allowance demand ( $D_{ETS}$ ).

<sup>8</sup> Since we work with only green and brown energy sources, the value of emission intensity parameter is assumed to be fixed. In reality, the emission intensity of brown energy sources varies, which implies that the demand for emission allowances depends also on the type of brown energy source. Higher value of  $\lambda_{ETS}$  will increase the demand for emission allowances.

We combine theoretical derivations and graphical illustrations of analysed markets to examine the effects of four key structural shocks on the electricity and emission allowance markets. First, we rewrite the two key equations. We defined the electricity demand as:

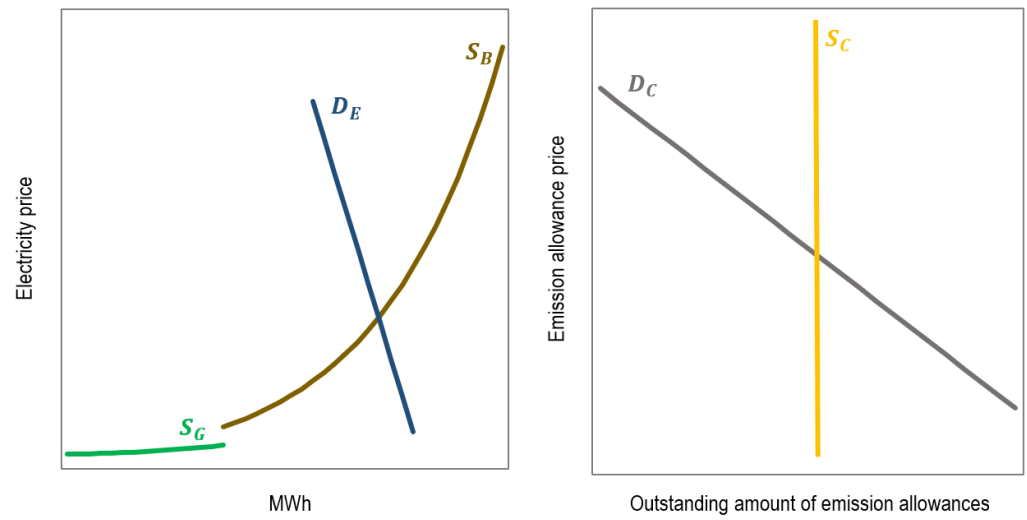
$$D_E = p_E^{-\alpha} \sum_{i=1}^I \left( \frac{\theta_i}{\mu_i} \right)^\alpha. \quad (1)$$

The market price of electricity equals:

$$p_E = \frac{p_L + p_{ETS} \lambda_{ETS}}{\beta_{AL} \beta - 1}. \quad (2)$$

The following structural shocks are examined: electricity demand shock, an emission allowance market shock, an adverse brown supply shock and an adverse green supply shock.

Figure 1: **Graphical representation of electricity and emission allowance markets**



A positive electricity demand shock represents an unexpected increase in electricity demand (e.g., a sudden increase of economic activity). In our theoretical model, this shock is captured by an increase in the  $\theta_i/\mu_i$  ratio, which reflects a higher marginal utility of electricity consumption. According to Equation 1, an increase in this ratio shifts electricity demand curve ( $D_E$ ) rightwards. Given the merit order assumption in our model (i.e., the marginal bid is submitted by the brown energy-based electricity producer), the additional demand is met by increased electricity production from brown energy sources, which results in higher wholesale electricity price. The price rise is further supported by developments in the emission allowance market. As residual electricity demand is produced from brown energy sources, the demand for emission allowances and their prices increase due to higher GHG emissions, which amplifies the wholesale electricity price increase due to larger per-unit emission allowance add-on. Graphically, the positive demand shock is represented by a rightward shift in both the electricity ( $D_E$ ) and emission allowance ( $D_{ETS}$ ) demand curves (Appendix A.2, Figure A.2.1).

A positive emission allowance market shock may arise from either supply- or demand-side adjustment. On the supply side, policymakers may introduce measures to reinforce the credibility of decarbonisation objectives (e.g., "Fit for 55"<sup>9</sup>) by reducing the annual

<sup>9</sup> "Fit for 55" refers to the EU's plan for a green transition, which aims to reduce net GHG emissions by at least 55% by 2030 compared to the 1990 level (Ovaere and Proost, 2022).

issuance of allowances. On the demand side, financial institutions and other non-compliance market participants may exert influence through speculative trading activity (Ampudia et al., 2022).<sup>10</sup> Equation 2 implies that an increase in the emission allowance price ( $p_{ETS}$ ), following a shock in the emission allowance market, raises the wholesale price of electricity ( $p_E$ ). This reflects the additional cost burden of brown electricity producers for GHG emissions. As a result, electricity consumption declines due to its inverse relationship with price. The ensuing reduction in demand leads to lower brown electricity production, while electricity production from green energy sources remains unaffected, given that their marginal costs are not contingent on allowance prices. Graphically, the positive emission allowance market shock is illustrated by either a leftward shift in the supply curve ( $S_{ETS}$ ) or a rightward shift in the demand curve ( $D_{ETS}$ ) in the emission allowance market. Irrespective of whether the shock is supply- or demand-driven, the resulting increase in  $p_{ETS}$  raises the marginal cost of brown energy-based electricity production and shifts the brown electricity supply curve ( $S_B$ ) upward in the electricity market (Appendix A.2, Figure A.2.2).

An adverse brown supply shock raises the wholesale electricity price, albeit through different mechanism. This shock originates from an unexpected event that reduces available quantity of brown energy sources and simultaneously raises their price ( $p_L$ ): for example, a sudden increase in geopolitical tensions. Higher input costs drive up wholesale electricity price, as indicated by Equation 2. Note, the increase in electricity prices is partially offset by a lower add-on for emission allowances, as their price falls due to decreased production from brown energy sources ( $S_B$ ). Consequently, emission allowances act not only as a decarbonisation incentive but also as a buffer that dampens the impact of brown supply shocks.<sup>11</sup> Graphically, the negative brown supply shock is represented by leftward shifts in both the brown electricity supply curve ( $S_B$ ) and the emission allowance demand curve ( $D_{ETS}$ ) (Appendix A.2, Figure A.2.3).

Finally, the negative green supply shock captures an unexpected reduction in the supply of electricity produced from green energy sources. Recall, green electricity supply is given by:

$$S_G = \phi_G f(\overline{K_G}).$$

In our model, the negative green electricity supply shock may be caused by (i) a reduction in total installed amount of production capacities based on green energy ( $\overline{K_G}$ ), due to, for example, unforeseen equipment malfunctions, or (ii) adverse weather conditions (e.g., drought or low solar radiation) that reduce the utilisation parameter  $\phi_G$ . The resulting decline in green supply necessitates increased production from brown energy sources ( $S_B$ ) to meet electricity demand, thereby increasing both brown electricity production and GHG emissions. This raises demand for emission allowances and their price, which translates into higher marginal cost of brown electricity. Wholesale electricity price increases. Graphically, the negative green supply shock is depicted by a contraction of the green segment of the electricity supply curve ( $S_G$ ), an associated leftward shift in the brown supply curve ( $S_B$ ), and a rightward shift in the emission allowance ( $D_{ETS}$ ) demand curve (Appendix A.2, Figure A.2.4).<sup>12</sup>

<sup>10</sup> Speculative trading has a limited impact on the EU ETS allowance price, given the relatively small role of these participants. In 2021, the investment funds held less than 1.0% of the outstanding open positions. Additionally, an index that measures the speculation activity in the EU ETS futures market shows that, despite a limited increase between 2019 and 2021, the speculation activity remained well below the levels observed at the creation of the ETS market (Ampudia et al., 2022).

<sup>11</sup> This buffering effect is empirically confirmed by a counterfactual scenario presented in the results section 4.5.

<sup>12</sup> A sufficiently large positive green supply shock could potentially lead to negative prices due to oversupply. However, such scenarios are beyond the scope of this paper, as we focus on marginal adjustments in the electricity market. This focus is justified historically, as monthly electricity prices remained positive throughout our sample period (Figure 2, left). Nevertheless, as electricity production from green energy sources expands further, this issue may gain economic relevance.

## 3 Methodology and data

### 3.1 The empirical model

Our analysis employs a nonparametrically estimated time-varying coefficient VARX model with stochastic volatility.<sup>13</sup> The purpose is to allow the propagation of shocks to evolve smoothly with the electricity mix and the EU ETS environment, rather than to impose discrete regime breaks. A stable response is therefore an admissible empirical result, not a model failure.<sup>14</sup> The time-varying approach has been extensively applied in the literature that analyses the evolving structure of energy markets and economy in general. Notable contributions include works by Cogley and Sargent (2005), Primiceri (2005), Canova and Gambetti (2009), while Casas et al. (2021) provide a more general perspective on SURE models.

Let  $y_t$  be a vector containing three variables of interest (growth of wholesale electricity price, quantity of electricity produced from brown energy sources, and price of EU ETS emission allowances) and assume it satisfies:

$$y_t = A_{0,t} + A_{1,t}y_{t-1} + B_t Q_t^G + \varepsilon_t.$$

Or in compact form:

$$y_t = X_t \beta_t + \varepsilon_t$$

where  $A_{0,t}$  is a vector of time-varying intercepts,  $A_{1,t}$  is a matrix of time-varying autoregressive coefficients,  $B_t$  is a time-varying vector of effects of changes in green electricity production on endogenous variables, and  $\varepsilon_t$  is a vector of white noise errors with zero mean and time-varying variance covariance matrix  $\Sigma_t$ . In line with Casas et al. (2021), we further assume that diagonal elements of  $\Sigma_t$  can be written as  $\sigma(t/T)$ , where  $\sigma(u)$  are smooth enough functions.

The time-varying impulse response functions (IRFs) are defined as:

$$\Phi_t(L) = \sum_{k=0}^{\infty} \Phi_{k,t} L^k,$$

with  $\Phi_{0,t} = I_n$  and  $\Phi_{k,t} = S_{3,3}(A_t^k)$ , where  $A_t = A_{1,t}$  and  $S_{n,n}(X)$  is a function which selects the first  $n$  rows and  $n$  columns of matrix  $X$ . Further, we denote the Cholesky factor of  $\Sigma_t$  by  $C_t$  so that  $C_t C_t' = \Sigma_t$  and denote by  $Q_t$  be the randomly drawn orthogonal matrix that satisfies the identifying restrictions discussed in Section 3.3 so that  $Q_t Q_t' = I_3$ . The structural impulse responses are therefore defined as  $\Phi_t(L) C_t Q_t$  and the structural shocks are  $u_t = Q_t' C_t^{-1} \varepsilon_t$ .

Following Casas et al. (2021), we estimate the reduced form model by Nadaraya-Watson kernel regression estimator that, at time  $t$ , minimizes the following smoothed weighted sum of squared residuals,

$$\hat{\beta}_t \equiv \arg \min \sum_{s=1}^T (Y_s - X_s \beta_t)' K_{H,ts}^{1/2} \Sigma_s^{-1} K_{H,ts}^{1/2} (Y_s - X_s \beta_t)$$

where  $K_{H,ts} = \text{diag}(K_{h_1,ts}, \dots, K_{h_M,ts})$  and  $K_{h_m,ts} = (Th_m)^{-1} K((t-s)/Th_m)$  is the matrix of weights introducing smoothness according to the vector of bandwidths  $H =$

<sup>13</sup> Appendix A.1 provides diagnostic tests of the fixed parameter VAR model.

<sup>14</sup> Between 2010 and 2025 the share of electricity produced from green energy sources increased from 23% to 49% (IEA, 2026).

$(h_1, \dots, h_M)'$ .  $M$  pertains to the length of vector  $\beta_t$ . This minimisation procedure accounts for the time-varying structure of variance covariance matrix of errors,  $\Sigma_t$ . The solution to the optimization problem presented above is the vector of estimated coefficients at time  $t$ :

$$\hat{\beta}_t = \left( \sum_{s=1}^T X_s' K_{H,ts}^{1/2} \Sigma_s^{-1} K_{H,ts}^{1/2} X_s \right)^{-1} \sum_{s=1}^T X_s' K_{H,ts}^{1/2} \Sigma_s^{-1} K_{H,ts}^{1/2} Y_s$$

### 3.2 Data

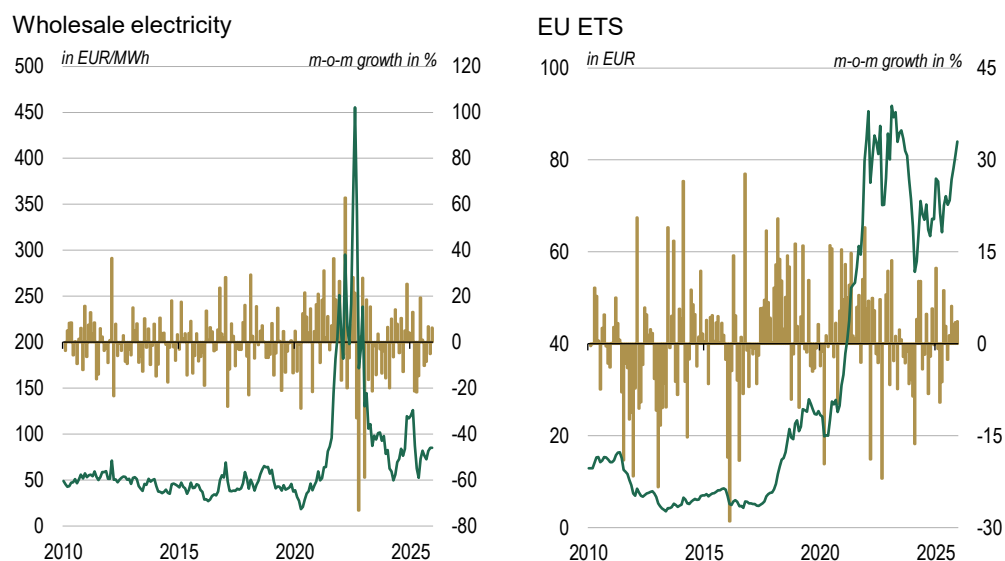
The model is estimated using seasonally adjusted monthly growth rate data spanning the period from February 2010 to December 2025. Figures 2 and 3 illustrate the developments in the model variables both as non-seasonally adjusted price or generation levels and seasonally adjusted month-on-month growth rates that are used for the estimation. Specifically, we utilise data on European wholesale electricity prices and EU ETS allowance prices. Electricity production data are obtained from the International Energy Agency (IEA) database. We focus on electricity generation in the euro area countries. Green electricity production is defined as the aggregate output from hydro-power, wind, solar, geothermal, combustible renewables, and other renewable energy sources. In contrast, brown electricity production is derived residually as the difference between total electricity consumption and electricity generated from green energy sources. It comprises electricity produced from coal, peat, manufactured gases, nuclear energy, oil and petroleum products, natural gas, other combustible non-renewables, and nuclear power.<sup>15</sup>

The quantity and proportion of electricity generated from green energy sources have increased steadily over the observed period. Between 2010 and 2025, total annual green electricity production in OECD Europe more than doubled, reaching 1,079 TWh,<sup>16</sup> while the share of electricity generated from green energy sources rose by 24 percentage points, attaining 49% of total production. While electricity prices exhibited considerable volatility even in the early years of the sample, this volatility intensified markedly following the onset of the COVID-19 pandemic. As lockdown measures were implemented to contain the spread of the virus, electricity prices declined sharply, reaching a trough of 18.4 EUR per MWh in April 2020. Prices subsequently rebounded with the reopening of the economy, and the escalation of geopolitical tensions, particularly the Russian invasion of Ukraine, further accelerated the upward trend (Figure 2, left). In relation to EU ETS allowance prices, the early part of the sample is characterised by sustained stagnation at low levels, with an average of 8.8 EUR per tonne of CO<sub>2</sub> emissions between 2010 and 2015. However, in early 2018 allowance prices began to rise (Figure 2, right). This upward trend coincided with policy reforms and tightening of supply conditions.

<sup>15</sup> Nuclear is low-direct-emission baseload generation and need not be marginal, its inclusion therefore weakens a literal mapping between the empirical residual and the model's emissions-intensive brown technology.

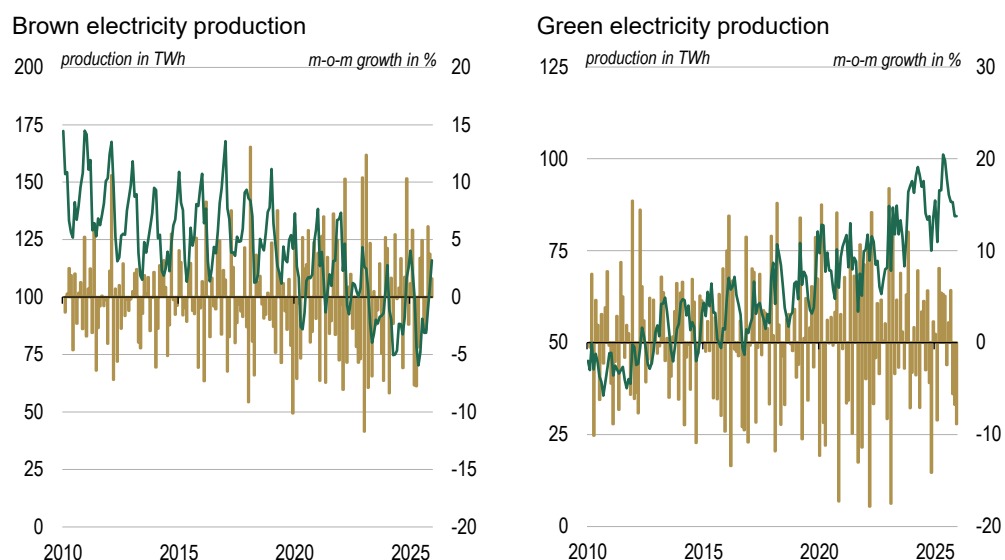
<sup>16</sup> By describing the annual level of production, the seasonal patterns disappear. Note that electricity production, especially from green energy sources, is subject to substantial seasonal variations.

Figure 2: **Wholesale electricity and EU ETS market price**



Note: The figures present non-seasonally adjusted levels (green line, left-hand axis) and seasonally adjusted monthly growth rates (gold columns, right-hand axis). Source: Bloomberg.

Figure 3: **Electricity production from brown and green energy sources**



Note: The figures present non-seasonally adjusted levels (green line, left-hand axis) and seasonally adjusted monthly growth rates (gold columns, right-hand axis). Source: IEA.

### 3.3 Structural identification

In analysing the electricity and emission allowance markets, it is important to distinguish between various shocks as their impacts can differ significantly in both persistence and intensity. Commodity markets literature emphasizes the complexity of factors, including technological advancements, regulatory changes, geopolitical events, and environmental policies, each of which can generate distinct types of shocks and associated impacts (Pindyck, 1999; Hamilton, 2009). These diverse shocks can have varied temporal impacts: some may lead to transient price fluctuations, while others might induce longer lasting changes in the market. Therefore, a more detailed analysis that looks closer into these individual shocks has a potential to provide clearer insights into their specific roles and consequences for different components of electricity market.

Building on these findings, this section introduces a structural identification scheme based on theoretically plausible sign restrictions. This approach will enable us to identify three fundamental structural shocks that impact the wholesale electricity and emission allowance markets. Specifically, we identify electricity demand shock, emission allowance market shock, and brown supply shock. Table 1 provides a summary of the corresponding sign restrictions. All restrictions are imposed only on impact. Appendix A.2 provides graphical representation of structural shocks.

Table 1: **Sign restrictions**

|                                                          | Electricity Demand | Emission Allowance | Brown Supply |
|----------------------------------------------------------|--------------------|--------------------|--------------|
| Wholesale electricity price growth                       | +                  | +                  | +            |
| EU ETS allowance price growth                            | +                  | +                  | -            |
| Growth of electricity produced from brown energy sources | +                  | -                  | -            |

Note: Signs in this table show restrictions imposed on the matrix B to identify Electricity demand, Emission Allowance, and Brown Supply shocks. (+) and (-) signs imply a positive and negative response to a particular shock, respectively. Restrictions are imposed only on impact.

The positive electricity demand shock (Table 1, column Electricity Demand; Appendix A.2, Figure A.2.1) stems from, for example, higher industrial production or elevated consumption of electricity by households. This shock raises the production of brown energy-based electricity producers, which results in higher wholesale electricity prices and increased demand for, and consequently prices of, emission allowances.

The positive emission allowance market shock (Table 1, column Emission Allowance; Appendix A.2, Figure A.2.2) originates either from regulatory tightening (e.g., reductions in allowance issuance) or speculative activity of market participants. An increase in the price of emission allowances elevates the marginal cost of electricity production from brown energy sources. This, in turn, raises wholesale electricity prices and leads to a contraction in electricity demand. Consequently, the output of electricity from brown energy sources declines.

The negative brown supply shock (Table 1, column Brown Supply; Appendix A.2, Figure A.2.3) is triggered by disruptions to the availability of brown energy inputs, due to, for example, heightened geopolitical tensions or disturbances in global energy supply chains. These disruptions elevate the prices of underlying commodities (e.g., oil or natural gas) and increase the marginal costs of electricity generation from brown energy sources. Higher marginal bids submitted by brown electricity producers lead to higher wholesale electricity price. Higher electricity prices lower demand, which reduces the electricity output by brown energy sources. This, in turn, depresses the demand for emission allowances and their price, which reduces marginal production costs of brown energy-based electricity producers. Hence, the effect of elevated input prices on wholesale electricity prices, originating from a brown supply shock, is partially mitigated by the buffering effect of lower emission allowance prices.

## 4 Results

In this section, we present the results. First, we discuss the average responses of model variables to identified structural shocks and relate them to our theoretical model. Next, we analyse how the impact of shocks on wholesale electricity and emission allowance price growth evolved over time. Third, we identify factors that influenced past developments of the electricity and emission allowance prices. Finally, we present a counterfactual scenario to illustrate how the emission allowance markets affected the dynamics of wholesale electricity prices in comparison to a fixed taxation of emissions.

#### 4.1 The average impact of structural shocks

We first compute the average of the time-varying IRFs across all horizons to capture the general dynamics of the model. The results indicate the transitory nature of the identified shocks. Appendix A.3 reports the average IRFs, where all responses are normalised such that each structural shock raises the median electricity price growth by one percentage point on impact, thereby ensuring comparability across shocks.

The electricity demand shock (Appendix A.3, column Electricity demand shock) increases the wholesale electricity and EU ETS allowance price growth, along with electricity production from brown energy sources. While the impact on the wholesale electricity and EU ETS allowance price growth on average dissipates after the first month, it remains statistically significant for the growth of electricity production from brown energy sources also in the second month after the shock. Then, the positive initial response is somewhat offset, reducing the overall impact on brown electricity production.

The median impulse response to the brown supply shock (Appendix A.3, column Brown supply shock) indicates that the initial increase in wholesale electricity price growth is offset somewhat in the second month following the shock. Consequently, the cumulative effect on the wholesale electricity price growth is on average smaller than that of the electricity demand shock. In addition, both the growth rate of electricity production from brown energy sources and the growth rate of the emission allowance price decline. The decline in brown electricity production growth is statistically significant only in the first month, whereas the reduction in emission allowance price growth remains statistically significant over a two-month horizon.

After the emission allowance market shock (Appendix A.3, column Emission allowance market shock), the increase in electricity price growth and decrease in production of electricity from brown energy sources also dissipate after the first month. Conversely, the response of the emission allowance price growth remains statistically significant and positive in the first three months after the shock. Our results indicate that the average median response of brown electricity production growth to the brown supply shock is slightly less pronounced than its response to the emission allowance market shock. Additionally, emission allowance prices exhibit a considerably stronger reaction to the emission allowance market shock compared to the brown supply shock.

Finally, column Green supply shock in Appendix A.3 displays the impulse response functions of the green supply shock. Due to its exogenous nature, the green supply shock requires no identifying restrictions. However, the model's implied responses are aligned with our theoretical expectations. A decline in green electricity production necessitates increased generation from brown energy sources to meet residual demand. This shift raises the demand for emission allowances and, consequently, their market price, due to the associated increase in greenhouse gas emissions. In addition, electricity prices rise as producers must activate brown generation units with higher marginal production costs, which are typically located further along the merit-order curve.

The increase in emission costs further compounds the rise in marginal production costs for brown energy producers, thereby amplifying the overall price effect.

The average median impulse responses to our structural shocks provide empirical validation for several mechanisms embedded in our theoretical model. In particular, both negative green and brown supply shocks lead to an increase in wholesale electricity price growth on impact, while the responses of the growth of electricity production from brown energy sources and EU ETS allowance price growth enables unique identification of the shock. Given the non-linear structure of the electricity supply curve, we first examine whether the magnitude of the electricity price response to shocks depends on the type of supply shock.

To this end, we calibrate the shocks such that the growth rate of electricity production from green or brown energy sources declines by one percentage point on impact. The results indicate that the price response is more pronounced following a brown supply shock. Specifically, a brown (green) supply shock that reduces brown electricity production growth by one percentage point raises wholesale electricity price growth by 5.5 (1.0) percentage points. This difference primarily reflects the composition of electricity generation in our sample. Since average electricity production from green sources is substantially lower than from brown energy sources in our sample (see Figure 3), a one percentage point decline in growth translates into a smaller absolute reduction in total electricity supply in the case of a green supply shock. Once this production base disparity is accounted for, the difference in price responses becomes more muted and aligns more closely with the model's supply-side cost dynamics.

Second, we examine the sensitivity of the electricity cost function with respect to its two main components: fuel and emission allowance prices. Both enter the wholesale electricity cost via Equation (2). We compare the effects of brown supply and emission allowance market shocks by calibrating each such that brown electricity production growth falls by one percentage point on impact. Following the emission allowance market shock, electricity price growth strengthens by 3.9 percentage points as emission allowance prices rise by 8.6 percentage points, leading us to conclude that the emission intensity parameter ( $\lambda_{ETS}$  in Equation 2) amounts to approximately 0.38 in historical data. This is broadly in line with the literature as emission intensity is between 0.3 and 0.5 and between 0.8 and 1.2 for natural gas and coal power plants, respectively (Quaschnig, 2025).

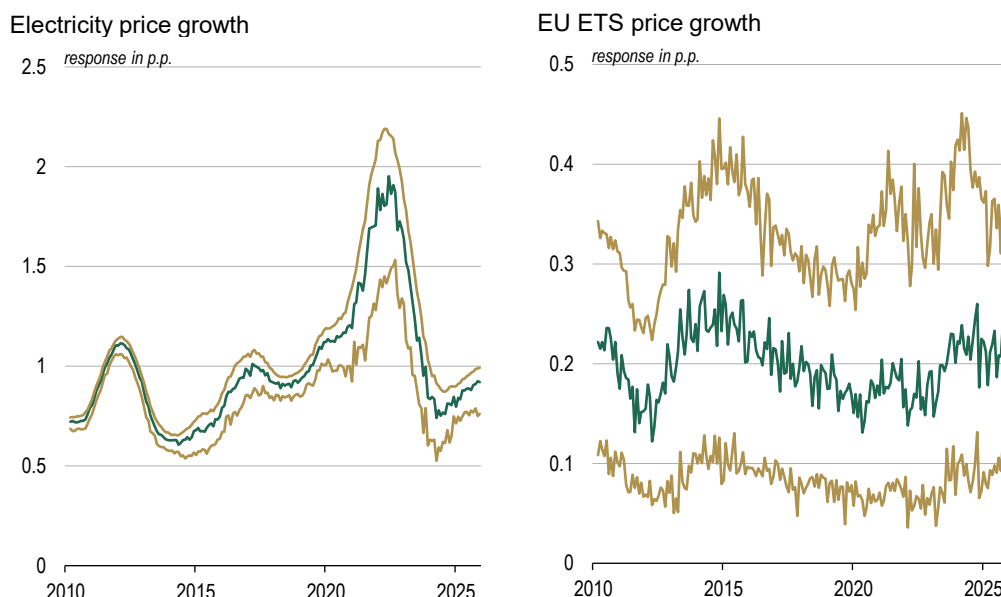
Following the brown supply shock, electricity price growth increases by 5.5 percentage points, while emission allowance price growth declines by 7.9 percentage points. As the change in cost of marginal energy source enters the wholesale electricity cost function directly we can see that the brown supply shock of this size reflects approximately 8.5 percentage point increase of the price of the marginal energy source. Additionally, the buffering effect of the ETS market reduces wholesale electricity price growth by around 3.0 percentage points. These results confirm the importance of joint assessment of distinct transmission channels (via fuel input costs and carbon pricing) that interactively determine wholesale electricity price movements.

We also assess whether the emission allowance price response is symmetric across different types of supply shocks. We calibrate the brown and green supply shocks such that both lead to a one percentage point decline in brown electricity production growth. The results show a markedly asymmetric response. The price of emission allowances declines by 7.8 percentage points in the case of a brown supply shock, but only by 0.3 percentage points following a green supply shock.

## 4.2 Time variation of the structural shocks' effects

The sensitivity of electricity and emission allowance markets to shocks has evolved over time, driven among other by the increasing share of green energy sources in electricity production and the tightening of climate policies. In our paper, this is reflected by the time variation of impulse responses at different horizons (see the Appendix A.4). For consistency, all responses in this section are normalised such that the median impact of a shock on electricity price growth equals one percentage point.

Figure 4: **Impact response to electricity demand shock**



Note: The green and gold lines denote median response and 68% confidence intervals in the period of shock. IRFs are normalised so that the median impact on electricity prices amounts to 1.0 p.p.

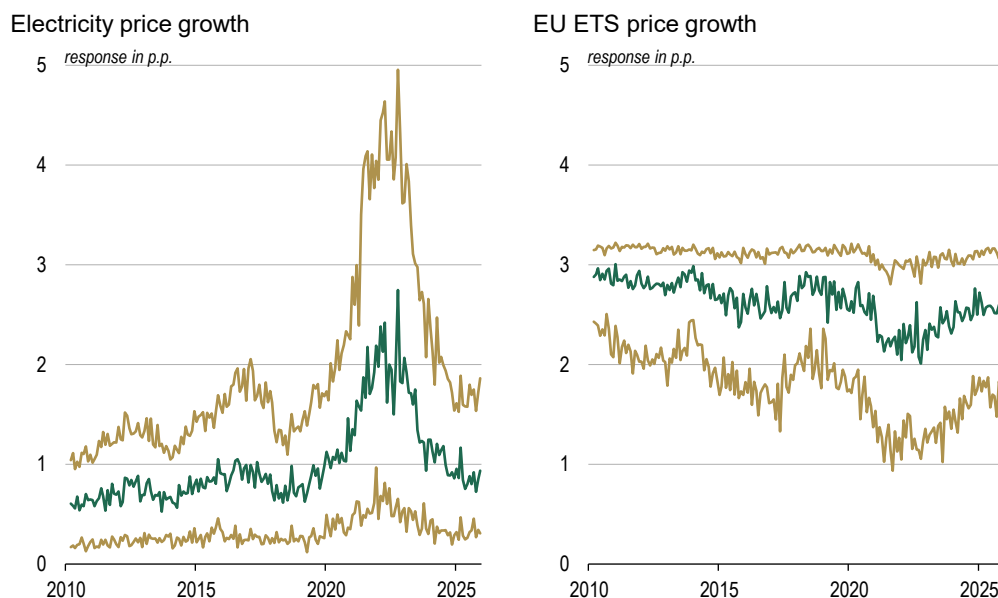
In general, the time-varying impulse responses align with the average impact of structural shocks and indicate a strong immediate reaction that dissipates rapidly in the months following the shock. This sub-section examines how the responses of two key variables of interest in our model – wholesale electricity and EU ETS allowance price growth – to identified structural shocks have changed over time.

The results show that the impact of all structural shocks on the wholesale electricity price growth has intensified over time as the share of electricity produced from green energy sources increased, whereas the immediate response of EU ETS allowance price growth has remained relatively stable. Conversely, the sensitivity of electricity price growth to shocks in electricity demand, brown energy supply, and emission allowances accelerated during the post-pandemic economic reopening, peaked in early 2022 with the onset of Russia's aggression against Ukraine, and declined afterwards. This marked rise in electricity price sensitivity reflects the steepening of electricity supply curve on account of scarcity and high prices of brown energy sources.

Figure 4 displays the impact response to an electricity demand shock. A positive electricity demand shock, which is driven by the shift in consumer preferences, increases electricity demand. Since marginal bid is submitted by the brown electricity producer even in the absence of the shock, additional demand is satisfied by further increase in electricity production from brown energy sources. This leads to higher GHG emissions and raises the EU ETS allowance price growth. The combined effect of higher emission

allowances and marginal production costs for brown electricity producers exerts upward pressure on electricity price growth. Our findings indicate that the median response of the wholesale electricity price growth to an electricity demand shock has been increasing already prior to the pandemic. However, after the pandemic, the sensitivity increased substantially as it reached levels almost double the median response in our sample. However, the sensitivity moderated towards sample average by the end of our sample (see Table and Figure A.4.1).

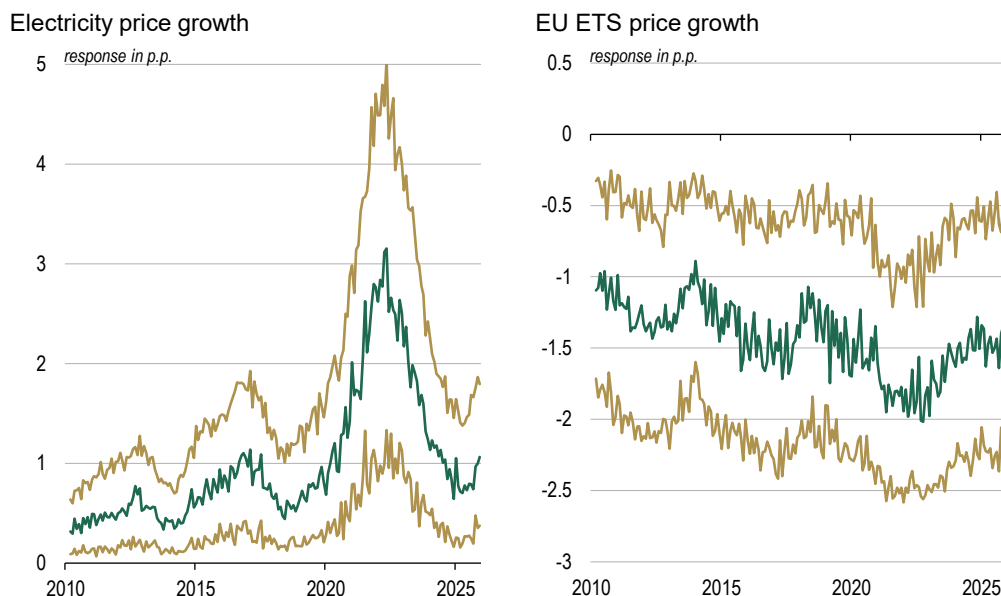
**Figure 5: Impact response to emission allowance market shock**



Note: The green and gold lines denote median response and 68% confidence intervals in the period of shock. IRFs are normalised so that the median impact on electricity prices amounts to 1.0 p.p.

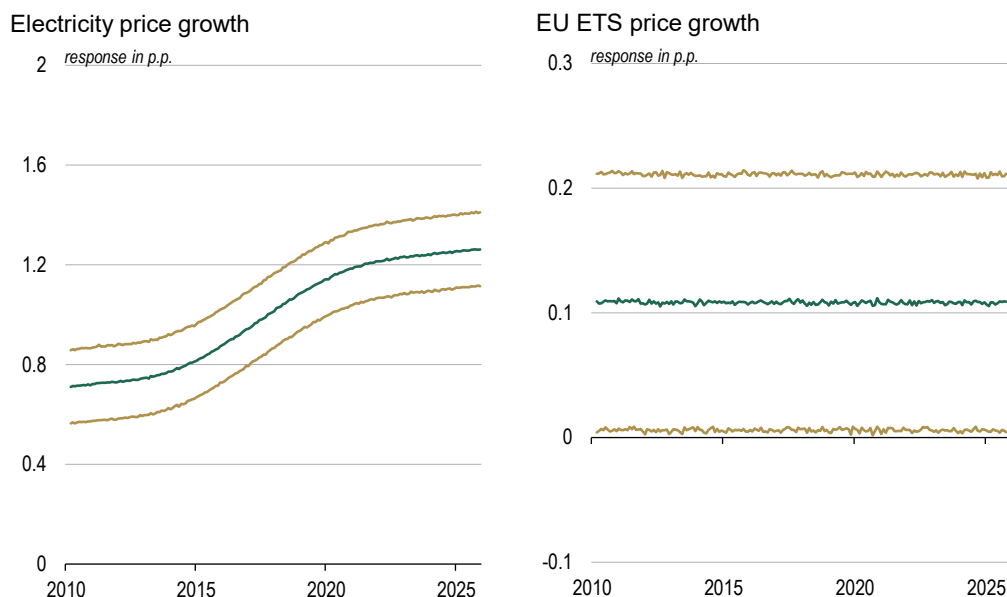
Figure 5 illustrates the immediate response of electricity and emission allowance price growth to an emission allowance market shock. The results reveal that the sensitivity of electricity price growth was relatively stable in the early part of the sample but increased significantly after the pandemic. While this sensitivity declined slightly towards the end of the sample, it remained above the pre-pandemic average. In contrast, the response of EU ETS allowance price growth remained stable throughout the sample period (see Table and Figure A.4.4).

Figure 6: **Impact response to brown supply shock**



Note: The green and gold lines denote median response and 68% confidence intervals in the period of shock. IRFs are normalised so that the median impact on electricity prices amounts to 1.0 p.p.

Figure 7: **Impact response to green supply shock**



Note: The green and gold lines denote median response and 68% confidence intervals in the period of shock. IRFs are normalised so that the median impact on electricity prices amounts to 1.0 p.p.

The response of electricity and emission allowance price growth to a brown supply shock is depicted in Figure 6. A negative brown supply shock, which is triggered by an unexpected reduction in electricity production from brown energy sources, accelerates wholesale electricity price growth and reduces EU ETS allowance price growth due to lower GHG emissions. Similar to previous shocks, the sensitivity of electricity price growth to brown supply shocks increased during the post-pandemic economic recovery and further intensified after the start of the Russian invasion of Ukraine disrupted the energy markets (see Table and Figure A.4.2).

Finally, we examine the response to a negative green supply shock, which is caused by a sudden decline in the supply of electricity from green energy sources. The response of endogenous model variables to green supply shocks required no further identifying assumptions, as the growth of electricity production from green sources within the same month is treated as exogenous in our model. Consequently, the responses are purely data driven. While no time variation was observed in the response of EU ETS allowance price growth, the sensitivity of electricity price growth to green supply shocks increased throughout the sample period. This aligns with our expectations given the growing importance of green energy sources in electricity production. By 2025, the share of electricity produced from green energy sources averaged at 49%, or 24 percentage points higher than in 2010 (IEA, 2024). Expansion of green energy-based electricity production capacities exerts a deflationary pressure on electricity price growth due to low marginal costs (see Table and Figure A.4.3).

### 4.3 Structural drivers of the wholesale electricity price

In this subsection, we present the decomposition of factors that affected the wholesale electricity price growth since the onset of the COVID-19 pandemic. Over the years, the growth of wholesale electricity price in the euro area has been subject to various structural shocks. They reflect the dynamic interplay between supply and demand factors, regulatory changes, and geopolitical events.

Figure 8 (left) depicts the contributions of identified structural shocks to wholesale electricity price growth in the euro area between 2019 and 2025. The wholesale electricity price was already declining prior to the pandemic. This was primarily due to the negative contribution of brown supply shocks, which reflected the conditions on the energy markets, and cooling electricity demand. Although the impact of negative brown supply shocks moderated somewhat in early 2020, the negative demand shocks that were caused by the outbreak of the COVID-19 pandemic accelerated the decline of the wholesale electricity price. With the gradual reopening of the economy, the reverse can be observed. Strong recovery of electricity demand is denoted by the positive contributions of electricity demand shocks, which were the key driver in the sharp increase of the electricity price growth in the post-pandemic period. Conversely, as the economic activity moderated, the negative electricity demand shocks began reducing the wholesale electricity price growth.

In the post-pandemic era, the wholesale electricity price growth was also supported by the positive contributions of emission allowance market shocks. These shocks were mainly related to the implemented regulatory changes, which strengthened the credibility of the carbon pricing mechanisms. For example, in 2021 the EU ETS entered its fourth phase, which is expected to last until 2030. In this phase, the linear reduction factor that determines the amount by which the cap will decline each year increased from 1.74% to 2.2% (European Commission, 2020). Faster reduction of the emission allowances supply supported the wholesale electricity price growth, due to higher marginal costs of brown energy-based electricity producers.

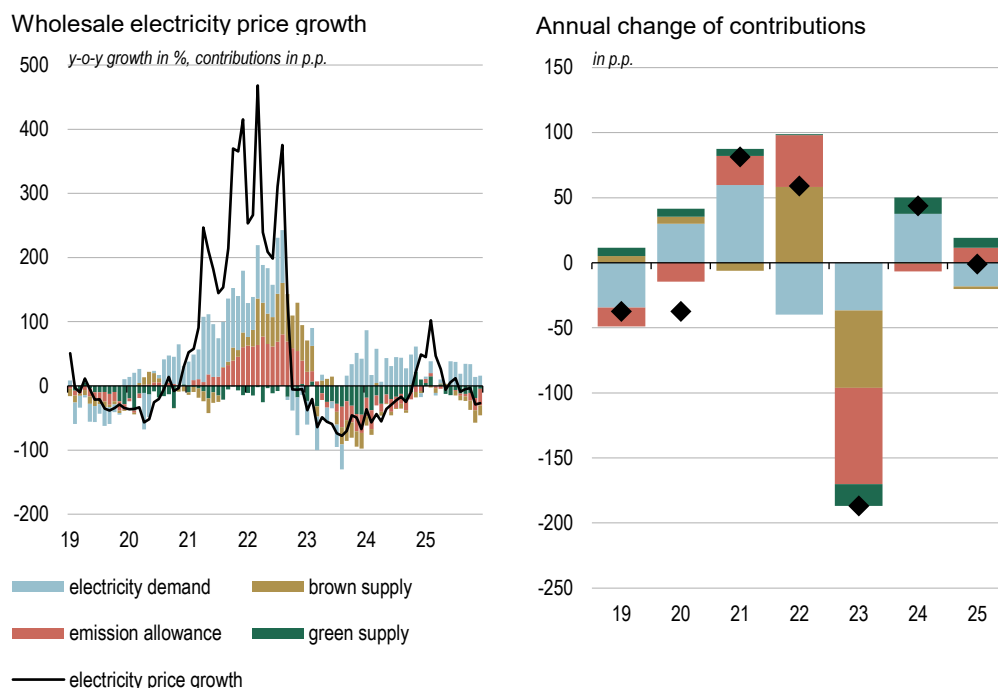
In 2022, the Russian invasion of Ukraine disrupted the supply of brown energy sources, which bolstered the wholesale electricity price growth. Although the impact of supply disruptions on the wholesale electricity price growth was significant, our analysis suggests that these effects dissipated fast and were not the key driver of the wholesale electricity price growth in the post-pandemic period. Conversely, the decline of whole-

sale electricity market price in 2023 was supported by the normalisation of energy markets, which is evident by the negative (change of) contributions of brown supply shocks (Figure 8, right).

Note that the wholesale electricity market price growth would be higher in the absence of positive green supply shocks. The expansion of production capacities based on green energy sources has a dampening effect on the wholesale electricity price growth due to low marginal production costs. In other words, the ranking of electricity production capacities based on merit order suggests that increasing the production from green energy sources induces a rightward shift of the electricity supply curve and reduces the wholesale electricity price growth.

While a rising share of electricity produced from green energy sources reduces wholesale electricity price growth, it also introduces potential risks. Rintamäki et al. (2017) find that wind generation reduced daily price volatility in Denmark but increased it in Germany because production patterns and system flexibility differed. Liebensteiner et al. (2025) likewise show that expansion of production from renewable energy sources can lower average prices even when gas, allowance prices and demand keep price levels elevated. Our results suggest that the sensitivity of wholesale electricity price growth to green supply shocks has increased over time, but their overall contribution remains limited. Given the stochastic and weather-dependent nature of green electricity production, such as its reliance on solar radiation or wind conditions, increasing share of electricity production from green energy sources may heighten the volatility of the wholesale electricity price growth. Absent significant advances in energy storage technologies and an expansion of storage capacity, this volatility is likely to persist or intensify in the future.

Figure 8: **Decomposition of wholesale electricity price growth**



Note: The left chart shows the contributions of identified structural shocks to year-on-year growth in the wholesale electricity price. The right chart displays changes in the average annual contribution of these shocks to wholesale electricity price growth.

#### 4.4 Structural drivers of the EU ETS allowance price

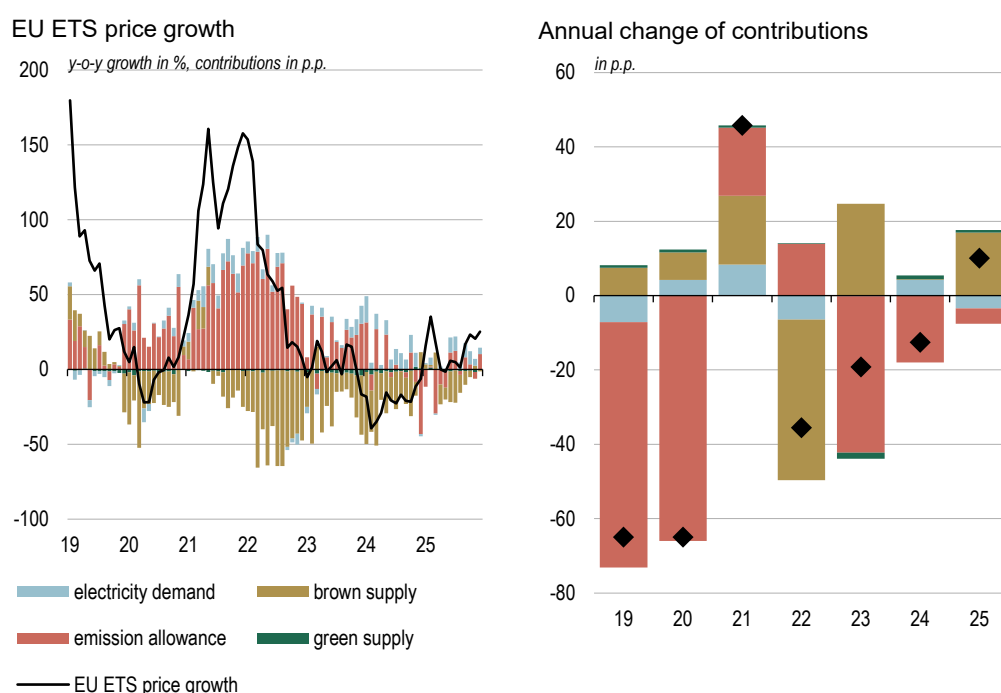
To understand developments in the euro area wholesale electricity market, it is essential to identify the primary drivers of EU ETS allowance price growth. The EU ETS allowance is the European Union's central instrument for reducing GHG emissions and addressing climate change. This section examines past determinants of the EU ETS allowance market price growth, with Figure 9 presenting its historical decomposition.

In the post-pandemic period, regulatory changes, aimed at enhancing the credibility of climate policy, emerged as the principal driver of emission allowance price growth, as reflected in the significant positive contributions of emission allowance market shocks. Additionally, electricity demand shocks, linked to the robust recovery of economic activity following the pandemic, also strengthened EU ETS allowance price growth. Conversely, the expansion of electricity production from green energy sources tempered emission allowance price growth, albeit with a relatively limited effect (Figure 9).

Negative brown supply shocks, which increase the market prices of brown energy source and reduce their supply, moderated emission allowance price growth in 2022. These shocks largely offset the upward pressure on prices caused by tighter climate policies and higher electricity demand.

Our analysis indicates that the EU ETS emission allowance functions as an automatic stabiliser for brown supply shocks. According to our theoretical model, the lower price add-on for emission allowances decreases the market price of electricity and mitigates the impact of brown supply shocks on electricity price growth. In other words, without the emission allowance market, the effect of brown supply shocks on electricity prices would be more pronounced.

**Figure 9: Historical decomposition of the EU ETS allowance price growth**



Note: The left chart shows the contributions of identified structural shocks to year-on-year growth in the EU ETS allowance price. The right chart displays changes in the average annual contribution of these shocks to EU ETS allowance price growth.

#### 4.5 Counterfactual scenario: fixed taxation of emissions

In policy debate, the effectiveness of market-based emission trading mechanism is often compared with fixed taxation approach (Pan et al., 2024). In this section, we contribute to this debate by examining the dynamics of electricity prices under two scenarios and highlighting the advantages of the market-based emission trading mechanism.

To model electricity price dynamics under the counterfactual fixed emission taxation scenario, we follow Kilian and Lewis (2011). Simply assuming the absence of emission allowance market shocks is insufficient as we must also account for how these allowances affect the transmission mechanisms of other shocks. We simulate a counterfactual scenario where changes of emission allowance price are immediately offset by ETS supply adjustments, effectively maintaining a constant cost for emission allowances (simulating fixed emission tax).

As with any stationary VAR model, we can express our model in terms of concurrent and past innovations:

$$y_t = \mu_t + \sum_{h=0}^H \psi_{t-h} \varepsilon_{t-h}$$

Here,  $\mu_t$  stands for initial conditions,  $\varepsilon_{t-h}$  denotes structural shocks and  $\psi_{t-h}$  represents the impulse response of  $N$  endogenous variables to  $K$  structural shocks at horizon  $h = 0, \dots, H$  estimated for period  $t = 1, \dots, T$ .

Let us define an array of baseline impulse response functions so that  $\psi_t \in \mathbb{R}^{N \times H \times K}$  is a three-dimensional object. We can further define  $\psi_t^k \in \mathbb{R}^{N \times H}$  as a matrix of impulse response functions pertaining to the shock  $k$ . We denote its counterfactual equivalent by  $\tilde{\psi}_t^k \in \mathbb{R}^{N \times H}$  for which we restrict the row pertaining to emission allowances (CP) to zero for every  $h = 0, \dots, H$ . We achieve that by finding a sequence of counterbalancing shocks in the emission allowance market ( $\gamma_h \forall h = 0, \dots, H$ ) recursively as follows:

For every  $h = 0, \dots, H$ :

$$\begin{aligned} \gamma_h &= \psi_{t,h}^{k,CP} / \psi_{t,1}^{CP,CP} \\ \tilde{\psi}_{t,h:H}^k &= \psi_{t,h:H}^k - \gamma_h \psi_{t,0:(H-h+1)}^{CP} \end{aligned}$$

Comparison of the counterfactual and baseline median impulse response functions is presented in Appendix A.5.

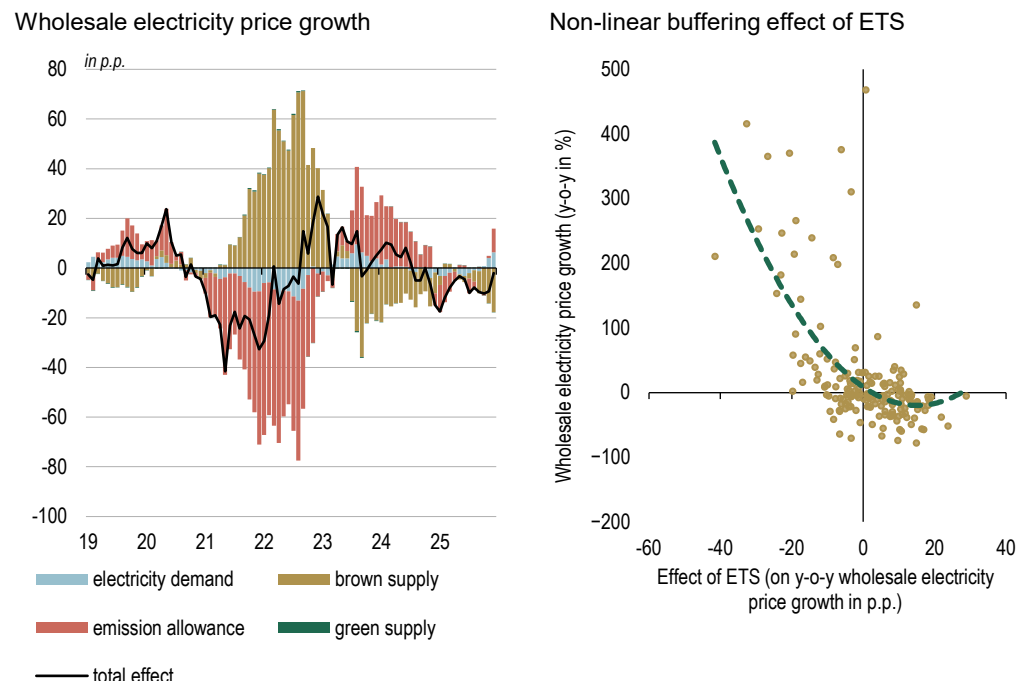
Figure 10 illustrates the total contribution of emission allowance trading system to electricity prices obtained as  $y_t - \tilde{y}_t$ . Total change accounts for direct contribution of emission allowance shocks and the altered transmission mechanism of other shocks.

Our estimates suggest that electricity prices in 2022 would have been lower in the absence of direct emission allowance market shocks (indicated by red bars). However, the negative effect is markedly counterbalanced by changes in the transmission mechanism of brown supply shocks (gold bars). In a fixed taxation scenario, these shocks would have a substantially larger impact on electricity prices (Figure 10, left). Thus, while the intuitive additional pressure on the electricity prices through the ETS market is evident, one has to consider the buffering mechanism of brown supply shocks that is provided by the existing ETS mechanism as opposed to the fixed taxation.

The ETS buffering against brown supply shocks can be explained as follows. When the supply of brown electricity sources diminishes and their prices rise, the production quantity of brown electricity decreases (as less energy is demanded at higher prices), leading to lower emission allowance prices. This, in turn, reduces production costs of

brown electricity producers, resulting in a slightly lower upward pressure on electricity prices. Additionally, the ETS penalizes electricity demand by amplifying the effects of such shocks on electricity prices, due to the increased steepness of the brown supply curve.

**Figure 10: Historical decomposition of the difference between the actual and counterfactual wholesale electricity price growth and the estimated buffering effects of ETS**



Note: The figure left displays the decomposition of the difference between actual and counterfactual wholesale electricity price growth, which assumes flat carbon tax. The figure right displays the estimated buffering effects on the x-axis in relation to the wholesale electricity price (y-axis). Scatter plot shows individual observations and the dashed green line shows the fitted quadratic curve.

## 5 Conclusion

Prior to the COVID-19 pandemic, the wholesale electricity price garnered relatively limited attention from euro area central bank policymakers, whose primary mandate is to ensure price stability. However, this dynamic shifted in the aftermath of the pandemic. Despite its relatively small weight in the consumer price index, the heightened volatility of wholesale electricity prices made their impact on headline inflation increasingly significant. Simultaneously, the price of emission allowances, designed to incentivise the reduction of carbon emissions and an important cost factor in electricity production, surged to record levels.

This paper examines post-pandemic developments in the wholesale electricity and emission allowance markets. To frame our empirical analysis, we first set-up a stylised partial equilibrium model of the electricity market that accounts for the composition of electricity production by source and the role of emission allowances. Empirically, we employ a time-varying VARX model with stochastic volatility, identified via sign restrictions, to capture structural shifts within the electricity market, particularly the increasing importance of green energy sources in electricity production.

Our findings yield several policy-relevant insights. First, we provide further evidence that the origin of shocks matters, a conclusion well established in the context of oil and exchange rate shocks. Second, our results stress the importance of employing a non-linear empirical framework to adequately capture evolving market dynamics. For instance, the impulse responses reveal that the sensitivity of both wholesale electricity price growth and brown energy production to green supply shocks has increased over time. This rising sensitivity highlights the importance of adequate storage technologies to mitigate price volatility arising from stochastic weather patterns affecting green electricity generation.

A historical decomposition of the euro area wholesale electricity price growth demonstrates that strong demand-side pressures, coupled with a tightening of emission allowance supply, were the main growth driver in the post-pandemic period. Although the energy supply disruptions triggered by Russia's invasion of Ukraine had an immediate and significant effect, the impact on wholesale electricity prices was relatively short-lived. Moreover, the historical decomposition reveals a negative contribution from the expansion of green electricity production, attributable to its lower marginal costs, which promotes further investment in power plants based on green energy sources.

Turning to EU ETS allowance price growth, its historical decomposition shows that regulatory reforms, which enhanced the credibility of climate policy, were the principal price growth drivers in the post-pandemic period, with demand recovery playing a supportive role.

We also find evidence that emission allowances act as a buffer against brown supply shocks. They function as an automatic stabiliser by mitigating the inflationary impact of brown supply shocks through a reduction in emission allowance costs. To further explore this buffering role, we simulate a flat-rate carbon tax counterfactual scenario. The results indicate that, in the absence of a market-based mechanism, such as the EU ETS, electricity price growth would have been substantially higher following brown supply shocks in 2022. Our findings reaffirm the dual role of the EU ETS in supporting decarbonisation goals while enhancing market stability amid supply-side disturbances.

While our empirical framework provides a robust analysis of the post-pandemic evolution of wholesale electricity and emission allowance markets, three limitations should be acknowledged. First, our analysis is based on monthly data, which may not capture intra-month or intra-day dynamics. Future research could assess whether our conclusions hold at higher-frequency settings. Second, we treat brown and green electricity sources as composite goods. Hence, we abstract from heterogeneity within each category (e.g., in terms of emission intensity or fuel price differentials). Future research could refine this classification to account for potential within-group variation, such as switching effects among brown sources. Third, our model assumes that the marginal bid is always submitted by a brown energy-based electricity producer. While this assumption holds for the sample period under study, future research should investigate how the results change if the marginal bid were consistently provided by green energy-based producers, given their increasing share in electricity generation.

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# Appendix

## A.1 Diagnostics of the fixed parameter VAR model

For the reference we share diagnostics related to fixed coefficient VAR model.

### ▪ Lag selection

The information criteria consistently propose one lag in the reduced-form VAR model. The restriction for the maximal lag order is set to 12. We followed these suggestions by including one lag in our VAR model specification.

Table A.1.1: **Lag selection criteria**

| AIC (n) | HQ (n) | SC(n) | FPE(n) |
|---------|--------|-------|--------|
| 1       | 1      | 1     | 1      |

### ▪ Serial autocorrelation of residuals

Asymptotic Portmanteau test of residual autocorrelation cannot reject the null hypothesis of no serial autocorrelation.

Table A.1.2: **Portmanteau Test (asymptotic)**

| Chi-squared | Degrees of freedom | p-value |
|-------------|--------------------|---------|
| 153.56      | 135                | 0.1309  |

### ▪ Residual normality

Multivariate Jarque-Bera test of normality of residuals concludes that the distribution of residuals is not normal. Consequently, our confidence intervals are estimated by the bootstrap.

Table A.1.3: **Multivariate Jarque-Bera test**

| JB-test (multivariate)       |                    |         |
|------------------------------|--------------------|---------|
| Chi-squared                  | Degrees of freedom | p-value |
| 52.417                       | 6                  | 0.0     |
| Skewness only (multivariate) |                    |         |
| Chi-squared                  | Degrees of freedom | p-value |
| 9.2889                       | 3                  | 0.03    |
| Kurtosis only (multivariate) |                    |         |
| Chi-squared                  | Degrees of freedom | p-value |
| 43.128                       | 3                  | 0.00    |

### ▪ OLS-CUSUM

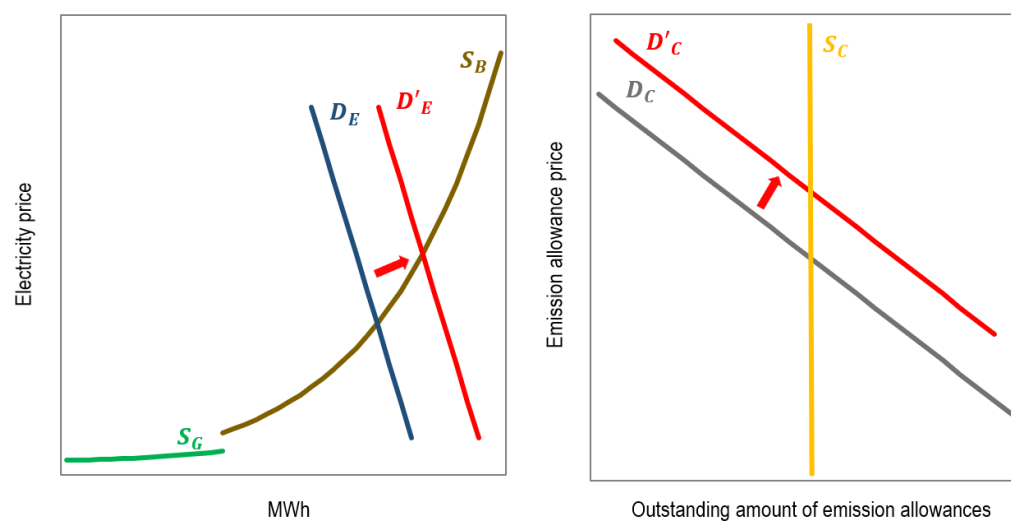
The test showed that there are no notable structural changes in the data.

The fixed-parameter diagnostics provide a useful reduced-form benchmark, but they do not test whether each structural impulse response evolves smoothly. In particular, a failure to reject parameter stability in the OLS-CUSUM diagnostic is not equivalent to evidence that every transmission coefficient is constant at every date. The time-varying specification allows, but does not force, gradual change. This distinction is visible in the results: the EU ETS allowance price response to green supply innovations is stable,

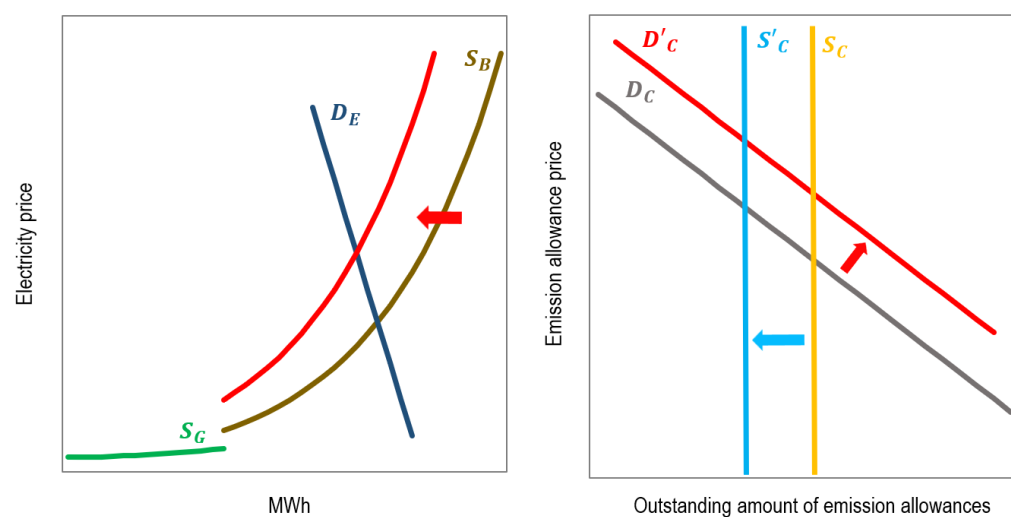
whereas wholesale electricity price responses strengthened around the 2021-2022 energy crisis and subsequently normalised. A fixed-coefficient VAR would compress these episode-specific movements into one sample-average response. We therefore use the fixed-parameter diagnostics as a benchmark for reduced-form adequacy and the time-varying model to describe economically relevant changes in transmission.

## A.2 Graphical representation of structural shocks

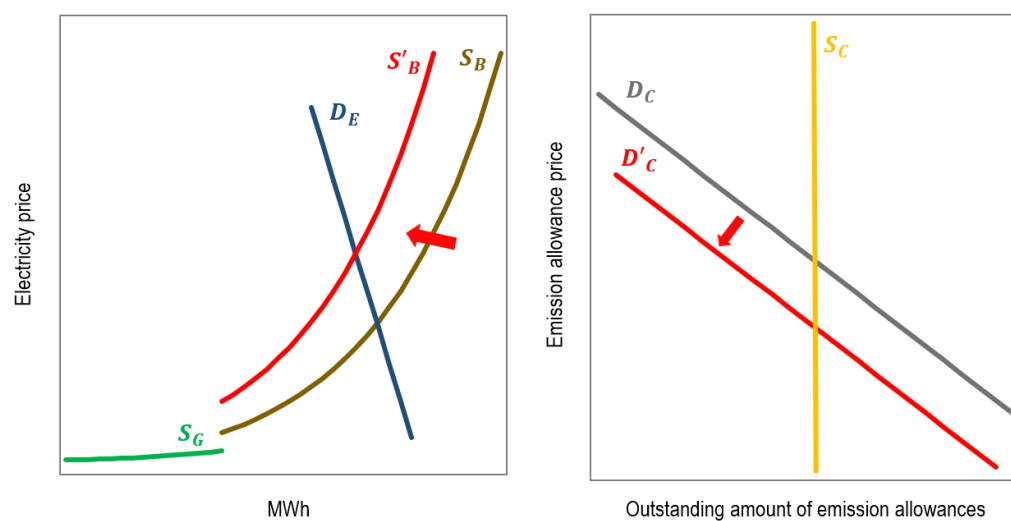
### Figure A.2.1 Electricity demand shock



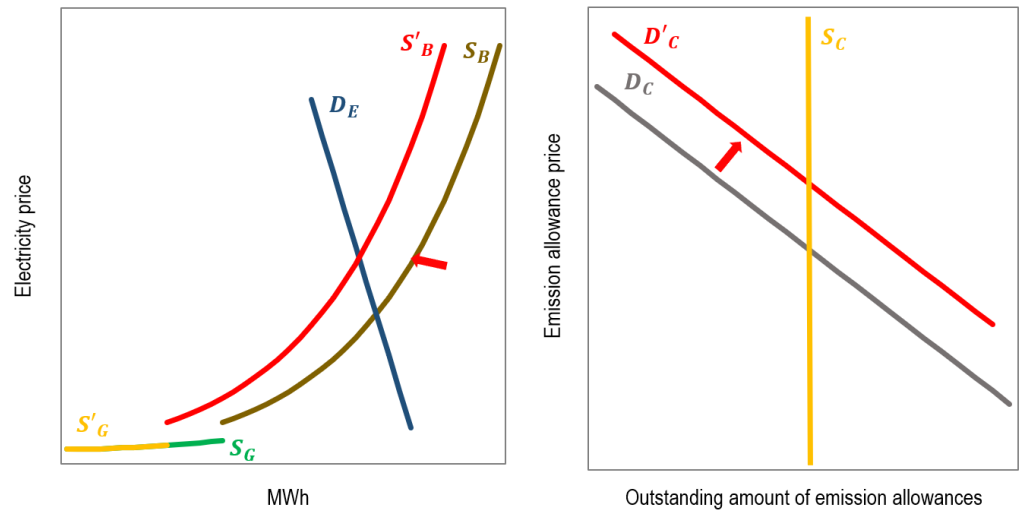
### Figure A.2.2 Emission allowance market shock



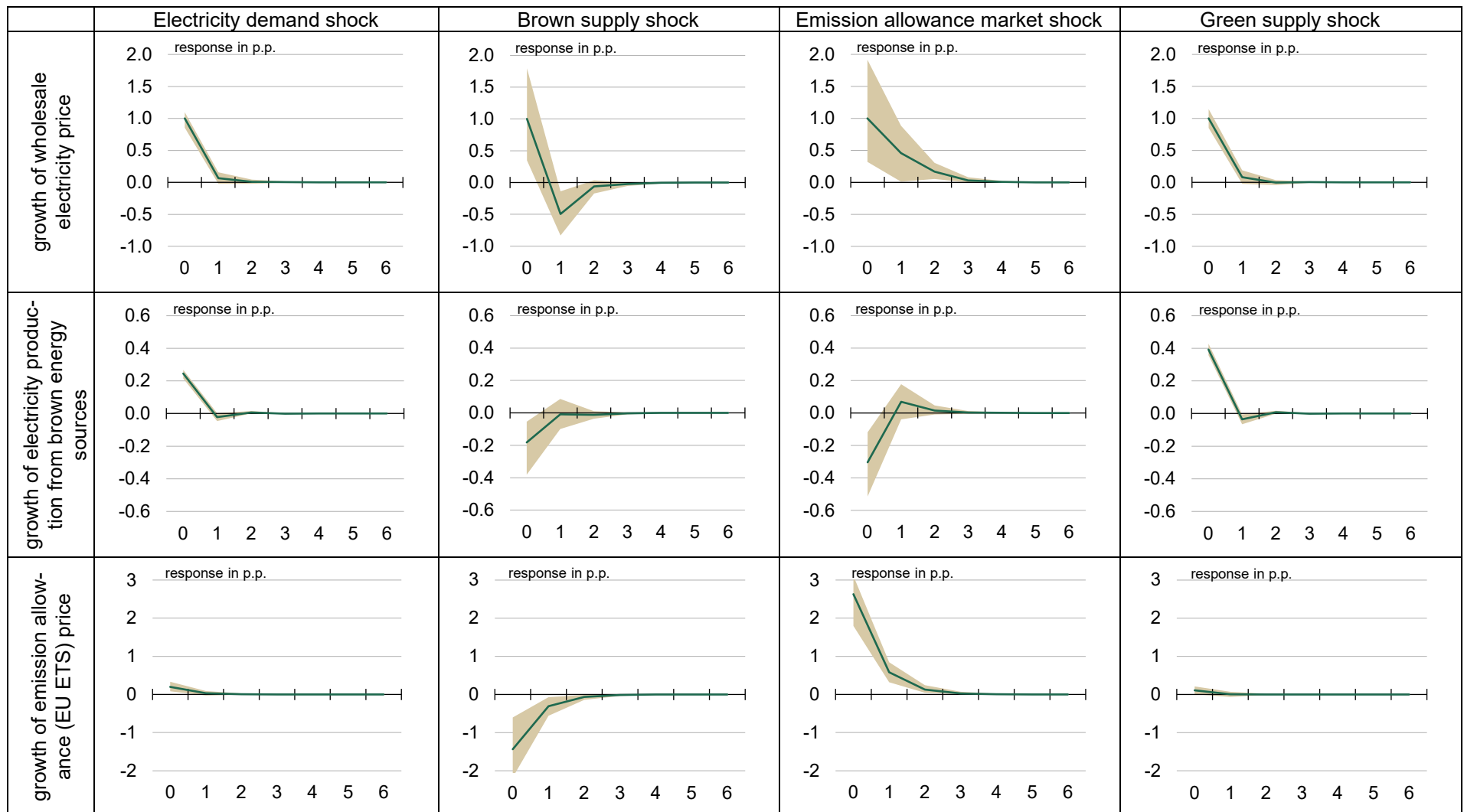
### Figure A.2.3 Brown supply shock



▪ **Figure A.2.4 Green supply shock**



### A.3 Average impulse response functions



The green and gold area denote the median response and 68% confidence intervals. IRFs are normalised so that the median impact on electricity prices amounts to 1.0 p.p.

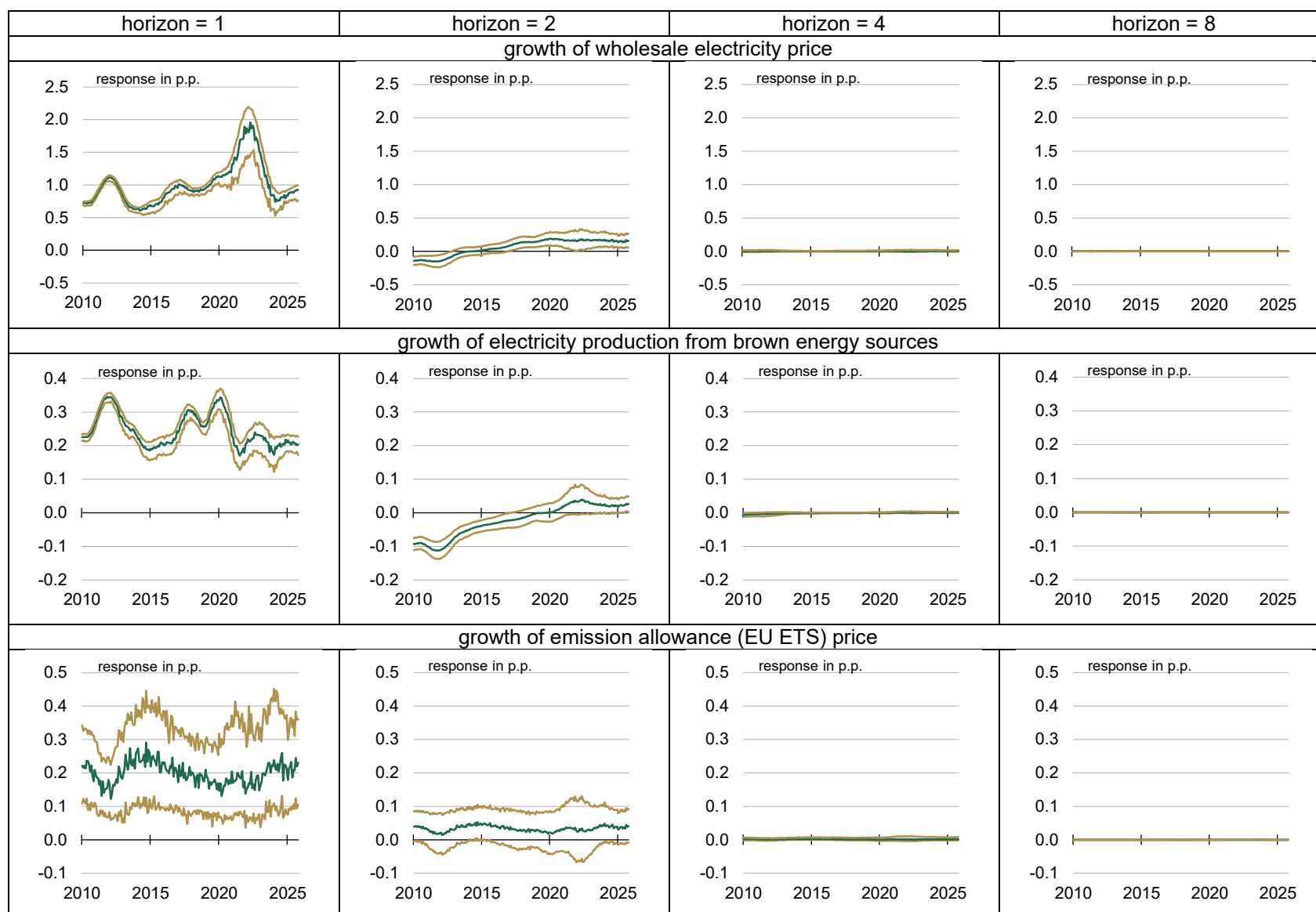
#### A.4 Time-varying impulse responses to structural shocks at various horizons

Table A.4.1: Time-varying IRFs to electricity demand shock

| growth of wholesale electricity price                      |       |       |       |       |       |       |       |       |       |      |      |      |      |      |      |      |
|------------------------------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|------|------|------|------|------|------|------|
| horizon                                                    | 2010  | 2011  | 2012  | 2013  | 2014  | 2015  | 2016  | 2017  | 2018  | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 |
| 1                                                          | 0.74  | 0.97  | 1.05  | 0.72  | 0.63  | 0.70  | 0.89  | 0.97  | 0.91  | 1.02 | 1.16 | 1.49 | 1.83 | 1.23 | 0.80 | 0.88 |
| 2                                                          | -0.14 | -0.15 | -0.12 | -0.03 | 0.00  | 0.02  | 0.05  | 0.10  | 0.14  | 0.16 | 0.18 | 0.16 | 0.17 | 0.17 | 0.16 | 0.15 |
| 3                                                          | 0.01  | 0.00  | -0.01 | -0.01 | -0.01 | -0.01 | 0.00  | 0.00  | 0.00  | 0.01 | 0.01 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| 4                                                          | 0.00  | 0.01  | 0.01  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 |
| growth of electricity production from brown energy sources |       |       |       |       |       |       |       |       |       |      |      |      |      |      |      |      |
| horizon                                                    | 2010  | 2011  | 2012  | 2013  | 2014  | 2015  | 2016  | 2017  | 2018  | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 |
| 1                                                          | 0.23  | 0.31  | 0.33  | 0.26  | 0.21  | 0.20  | 0.21  | 0.27  | 0.29  | 0.29 | 0.32 | 0.20 | 0.22 | 0.22 | 0.20 | 0.21 |
| 2                                                          | -0.09 | -0.11 | -0.10 | -0.07 | -0.05 | -0.04 | -0.03 | -0.02 | -0.01 | 0.00 | 0.01 | 0.03 | 0.04 | 0.03 | 0.02 | 0.02 |
| 3                                                          | 0.02  | 0.02  | 0.02  | 0.01  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 |
| 4                                                          | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| growth of emission allowance (EU ETS) price                |       |       |       |       |       |       |       |       |       |      |      |      |      |      |      |      |
| horizon                                                    | 2010  | 2011  | 2012  | 2013  | 2014  | 2015  | 2016  | 2017  | 2018  | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 |
| 1                                                          | 0.22  | 0.17  | 0.17  | 0.22  | 0.25  | 0.24  | 0.22  | 0.20  | 0.19  | 0.18 | 0.16 | 0.18 | 0.17 | 0.20 | 0.22 | 0.22 |
| 2                                                          | 0.04  | 0.02  | 0.02  | 0.04  | 0.05  | 0.05  | 0.04  | 0.03  | 0.03  | 0.03 | 0.02 | 0.03 | 0.03 | 0.03 | 0.04 | 0.04 |
| 3                                                          | 0.01  | 0.01  | 0.01  | 0.01  | 0.01  | 0.01  | 0.01  | 0.01  | 0.01  | 0.01 | 0.00 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 |
| 4                                                          | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

Values in the table denote the average median response in specific years at each horizon after the shock. IRFs are normalised so that the median impact on electricity prices amounts to 1.0 p.p.

▪ **Figure A.4.1: Time-varying IRFs to electricity demand shock**



The green and gold lines denote median response and 68% confidence intervals. IRFs are normalised so that the median impact on electricity prices amounts to 1.0 p.p.

▪ **Table A.4.2: Time-varying IRFs to brown supply shock**

| growth of wholesale electricity price |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|---------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| horizon                               | 2010  | 2011  | 2012  | 2013  | 2014  | 2015  | 2016  | 2017  | 2018  | 2019  | 2020  | 2021  | 2022  | 2023  | 2024  | 2025  |
| 1                                     | 0.38  | 0.47  | 0.60  | 0.49  | 0.48  | 0.73  | 0.93  | 0.88  | 0.57  | 0.77  | 1.14  | 2.19  | 2.69  | 1.80  | 1.03  | 0.85  |
| 2                                     | -0.11 | -0.16 | -0.23 | -0.22 | -0.22 | -0.29 | -0.36 | -0.42 | -0.42 | -0.54 | -0.68 | -0.83 | -0.91 | -0.88 | -0.82 | -0.83 |
| 3                                     | 0.05  | 0.06  | 0.06  | 0.04  | 0.02  | 0.01  | -0.01 | -0.03 | -0.05 | -0.08 | -0.12 | -0.17 | -0.19 | -0.19 | -0.19 | -0.19 |
| 4                                     | -0.01 | -0.01 | -0.01 | 0.00  | 0.00  | 0.00  | -0.01 | -0.01 | -0.02 | -0.02 | -0.03 | -0.05 | -0.05 | -0.05 | -0.04 | -0.04 |

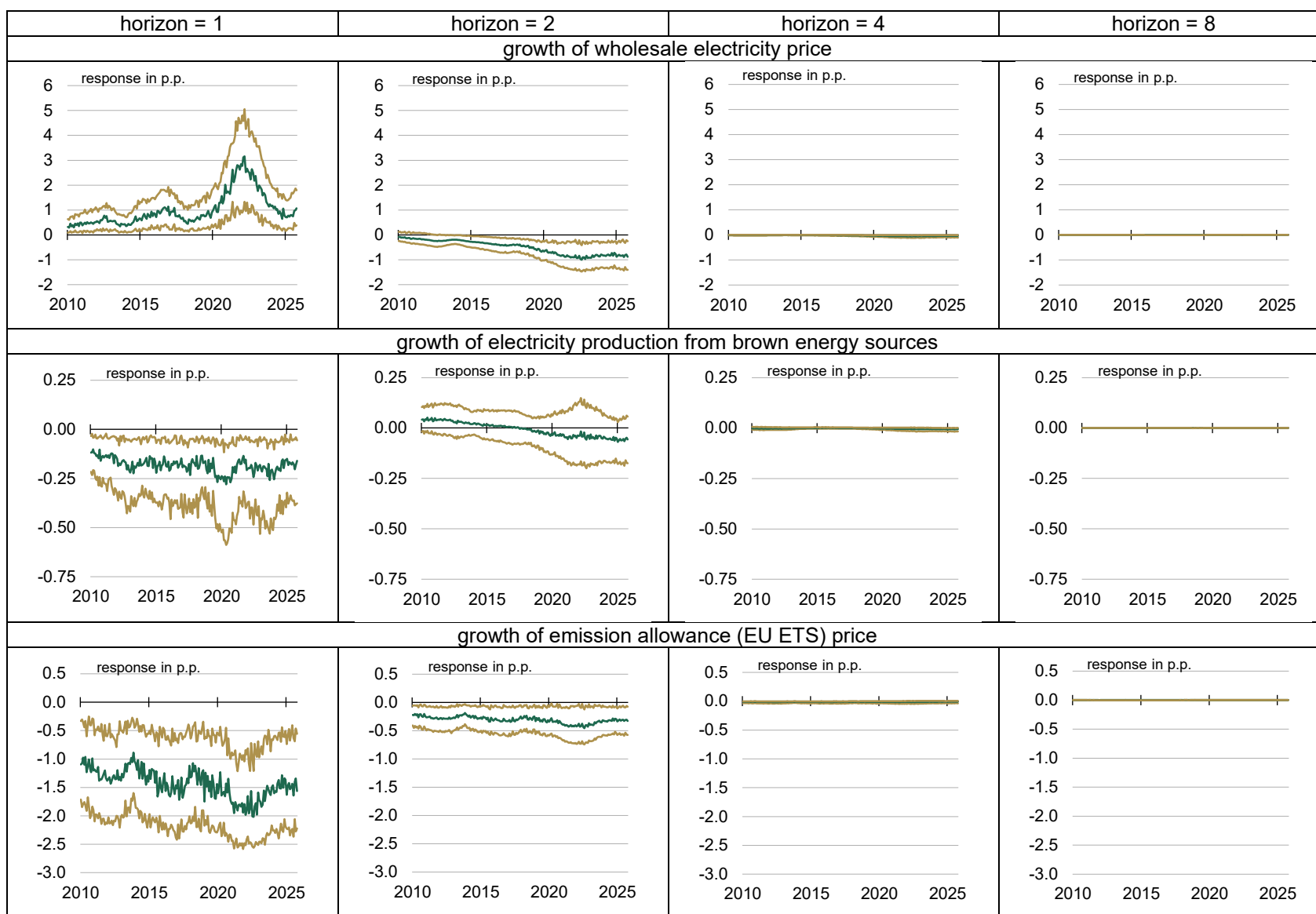
| growth of electricity production from brown energy sources |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|------------------------------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| horizon                                                    | 2010  | 2011  | 2012  | 2013  | 2014  | 2015  | 2016  | 2017  | 2018  | 2019  | 2020  | 2021  | 2022  | 2023  | 2024  | 2025  |
| 1                                                          | -0.13 | -0.14 | -0.17 | -0.19 | -0.17 | -0.18 | -0.18 | -0.19 | -0.17 | -0.21 | -0.25 | -0.18 | -0.20 | -0.20 | -0.20 | -0.17 |
| 2                                                          | 0.04  | 0.04  | 0.04  | 0.03  | 0.02  | 0.01  | 0.01  | 0.00  | -0.01 | -0.02 | -0.03 | -0.04 | -0.04 | -0.05 | -0.05 | -0.06 |
| 3                                                          | 0.01  | 0.01  | 0.02  | 0.02  | 0.01  | 0.01  | 0.00  | 0.00  | -0.01 | -0.02 | -0.02 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 |
| 4                                                          | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | -0.01 | -0.01 |

| growth of emission allowance (EU ETS) price |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|---------------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| horizon                                     | 2010  | 2011  | 2012  | 2013  | 2014  | 2015  | 2016  | 2017  | 2018  | 2019  | 2020  | 2021  | 2022  | 2023  | 2024  | 2025  |
| 1                                           | -1.10 | -1.24 | -1.35 | -1.18 | -1.17 | -1.34 | -1.50 | -1.52 | -1.28 | -1.45 | -1.53 | -1.81 | -1.87 | -1.69 | -1.51 | -1.48 |
| 2                                           | -0.23 | -0.26 | -0.29 | -0.25 | -0.25 | -0.29 | -0.32 | -0.32 | -0.28 | -0.30 | -0.33 | -0.40 | -0.42 | -0.37 | -0.33 | -0.31 |
| 3                                           | -0.05 | -0.06 | -0.06 | -0.05 | -0.05 | -0.06 | -0.07 | -0.07 | -0.06 | -0.06 | -0.07 | -0.08 | -0.08 | -0.08 | -0.06 | -0.06 |
| 4                                           | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 |

Values in the table denote the average median response in specific years at each horizon after the shock. IRFs are normalised so that the median impact on electricity prices amounts to 1.0 p.p.

▪ **Figure A.4.2: Time-varying IRFs to brown supply shock**



The green and gold lines denote median response and 68% confidence intervals. IRFs are normalised so that the median impact on electricity prices amounts to 1.0 p.p.

▪ **Table A.4.3: Time-varying IRFs to green supply shock**

| growth of wholesale electricity price |       |       |       |       |       |       |       |       |       |      |      |      |      |      |      |      |
|---------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|------|------|------|------|------|------|------|
| horizon                               | 2010  | 2011  | 2012  | 2013  | 2014  | 2015  | 2016  | 2017  | 2018  | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 |
| 1                                     | 0.72  | 0.73  | 0.74  | 0.76  | 0.79  | 0.85  | 0.91  | 0.98  | 1.05  | 1.12 | 1.17 | 1.20 | 1.23 | 1.24 | 1.25 | 1.26 |
| 2                                     | -0.11 | -0.09 | -0.06 | -0.03 | 0.00  | 0.04  | 0.08  | 0.12  | 0.16  | 0.19 | 0.21 | 0.21 | 0.19 | 0.17 | 0.13 | 0.09 |
| 3                                     | 0.00  | -0.01 | -0.01 | -0.02 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 |
| 4                                     | 0.00  | 0.01  | 0.01  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

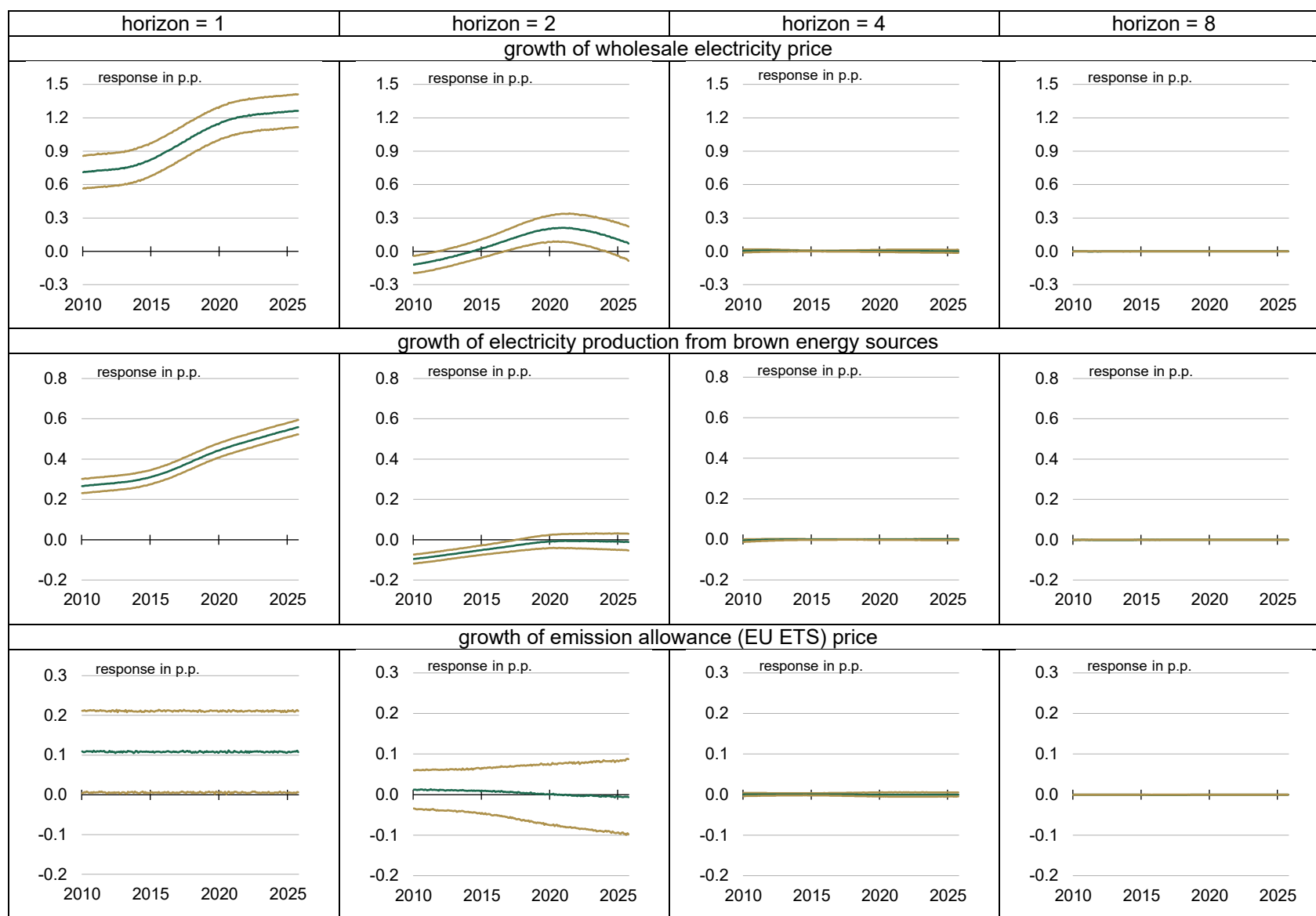
| growth of electricity production from brown energy sources |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|------------------------------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| horizon                                                    | 2010  | 2011  | 2012  | 2013  | 2014  | 2015  | 2016  | 2017  | 2018  | 2019  | 2020  | 2021  | 2022  | 2023  | 2024  | 2025  |
| 1                                                          | 0.27  | 0.28  | 0.28  | 0.29  | 0.30  | 0.32  | 0.34  | 0.37  | 0.40  | 0.43  | 0.45  | 0.47  | 0.49  | 0.51  | 0.53  | 0.55  |
| 2                                                          | -0.09 | -0.09 | -0.08 | -0.07 | -0.06 | -0.05 | -0.04 | -0.03 | -0.02 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 |
| 3                                                          | 0.02  | 0.02  | 0.01  | 0.01  | 0.01  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.01  | 0.01  | 0.01  | 0.01  | 0.01  | 0.01  |
| 4                                                          | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  |

| growth of emission allowance (EU ETS) price |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |       |
|---------------------------------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|-------|
| horizon                                     | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025  |
| 1                                           | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11  |
| 2                                           | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | -0.01 |
| 3                                           | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00  |
| 4                                           | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00  |

Values in the table denote the average median response in specific years at each horizon after the shock. IRFs are normalised so that the median impact on electricity prices amounts to 1.0 p.p.

▪ **Figure A.4.3: Time-varying IRFs to green supply shock**



The green and gold lines denote median response and 68% confidence intervals. IRFs are normalised so that the median impact on electricity prices amounts to 1.0 p.p.

▪ **Table A.4.4: Time-varying IRFs to emission allowance market shock**

| growth of wholesale electricity price |       |       |       |       |       |      |      |      |      |      |      |      |      |      |      |      |
|---------------------------------------|-------|-------|-------|-------|-------|------|------|------|------|------|------|------|------|------|------|------|
| horizon                               | 2010  | 2011  | 2012  | 2013  | 2014  | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 |
| 1                                     | 0.62  | 0.67  | 0.76  | 0.70  | 0.71  | 0.85 | 0.93 | 0.87 | 0.73 | 0.84 | 1.11 | 1.73 | 2.04 | 1.50 | 1.05 | 0.88 |
| 2                                     | -0.41 | -0.39 | -0.33 | -0.19 | -0.03 | 0.08 | 0.21 | 0.35 | 0.56 | 0.69 | 0.78 | 0.83 | 0.99 | 1.17 | 1.35 | 1.52 |
| 3                                     | 0.03  | 0.03  | 0.03  | 0.02  | 0.02  | 0.04 | 0.07 | 0.12 | 0.17 | 0.22 | 0.27 | 0.28 | 0.31 | 0.33 | 0.35 | 0.37 |
| 4                                     | -0.01 | -0.01 | 0.00  | 0.00  | 0.00  | 0.01 | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.05 | 0.06 | 0.07 | 0.07 | 0.08 |

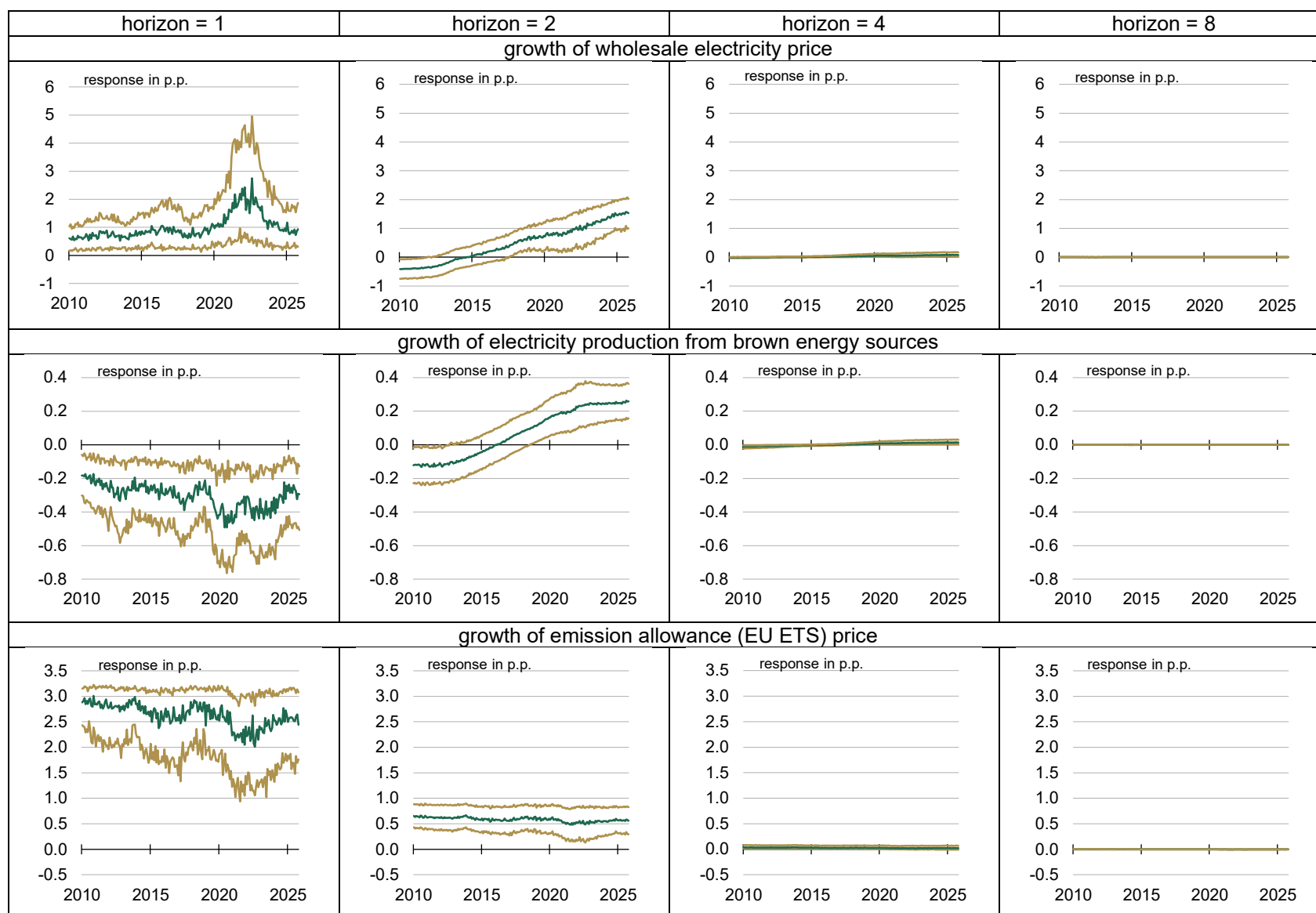
| growth of electricity production from brown energy sources |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|------------------------------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| horizon                                                    | 2010  | 2011  | 2012  | 2013  | 2014  | 2015  | 2016  | 2017  | 2018  | 2019  | 2020  | 2021  | 2022  | 2023  | 2024  | 2025  |
| 1                                                          | -0.20 | -0.23 | -0.28 | -0.27 | -0.25 | -0.27 | -0.28 | -0.33 | -0.28 | -0.31 | -0.43 | -0.38 | -0.38 | -0.39 | -0.33 | -0.27 |
| 2                                                          | -0.12 | -0.12 | -0.12 | -0.10 | -0.07 | -0.03 | 0.01  | 0.05  | 0.09  | 0.13  | 0.17  | 0.20  | 0.23  | 0.24  | 0.25  | 0.25  |
| 3                                                          | 0.01  | 0.01  | 0.00  | 0.00  | -0.01 | -0.01 | -0.01 | 0.00  | 0.01  | 0.02  | 0.02  | 0.02  | 0.03  | 0.04  | 0.05  | 0.06  |
| 4                                                          | -0.01 | -0.01 | -0.01 | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.01  | 0.01  | 0.01  | 0.01  | 0.01  | 0.01  | 0.01  |

| growth of emission allowance (EU ETS) price |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
|---------------------------------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| horizon                                     | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 |
| 1                                           | 2.90 | 2.87 | 2.80 | 2.85 | 2.80 | 2.63 | 2.62 | 2.62 | 2.81 | 2.71 | 2.62 | 2.27 | 2.26 | 2.39 | 2.54 | 2.58 |
| 2                                           | 0.64 | 0.63 | 0.62 | 0.63 | 0.62 | 0.58 | 0.57 | 0.58 | 0.61 | 0.60 | 0.59 | 0.51 | 0.52 | 0.54 | 0.56 | 0.57 |
| 3                                           | 0.15 | 0.15 | 0.15 | 0.15 | 0.14 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.12 | 0.10 | 0.10 | 0.10 | 0.11 | 0.11 |
| 4                                           | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |

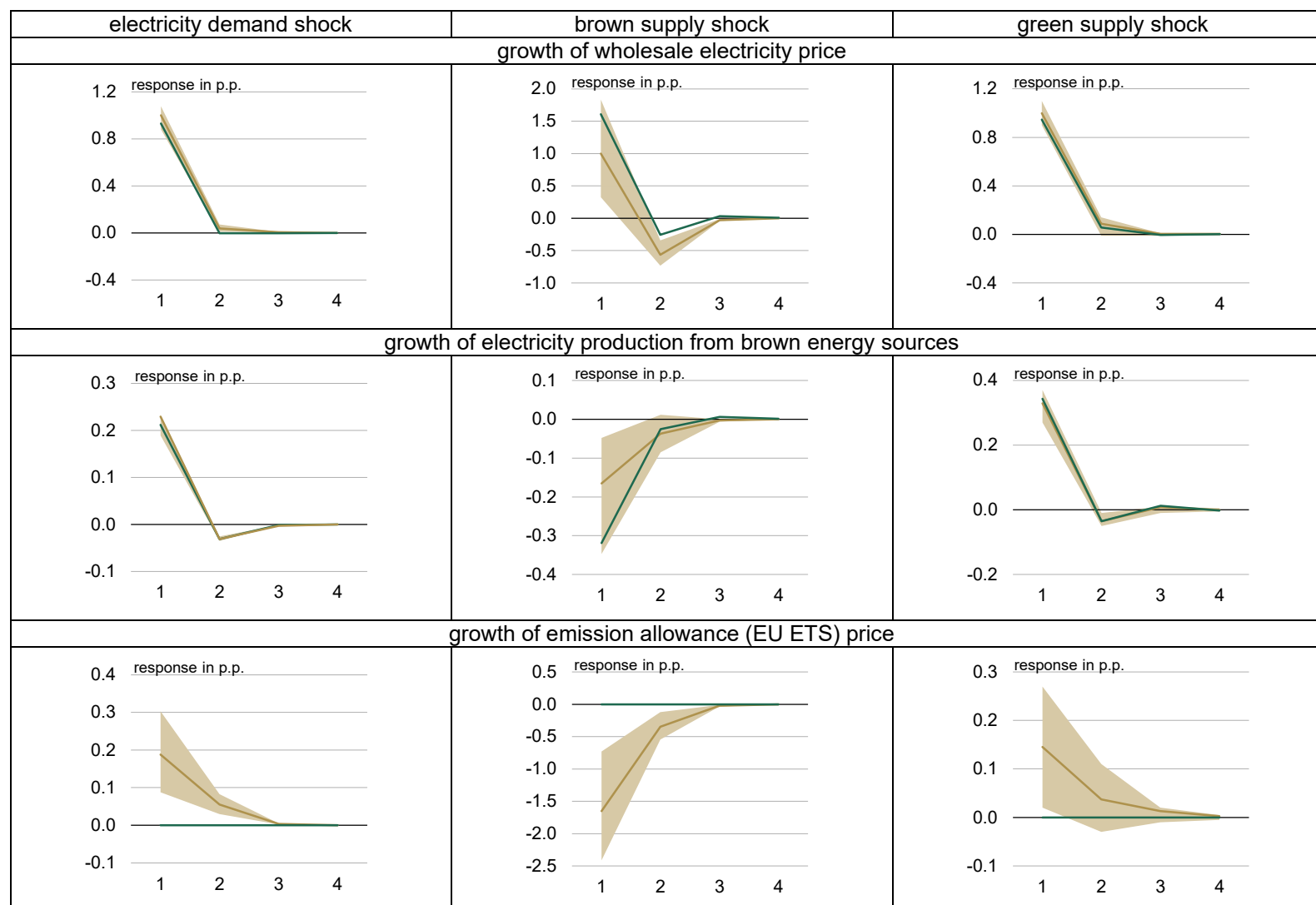
Values in the table denote the average median response in specific years at each horizon after the shock. IRFs are normalised so that the median impact on electricity prices amounts to 1.0 p.p.

▪ **Figure A.4.4: Time-varying IRFs to emission allowance market shock**



The green and gold lines denote median response and 68% confidence intervals. IRFs are normalised so that the median impact on electricity prices amounts to 1.0 p.p.

## A.5 Counterfactual impulse response functions



Note: The shocks are scaled to a 1 percentage point increase of wholesale electricity price growth on impact. Dark gold line displays the baseline average median IRFs, the shaded areas 68% confidence intervals, and green line the average median counterfactual impulse response to the respective shock.