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RELATION OF CO_2 EMISSION ALLOWANCE PRICES AND ELECTRICITY PRICES IN POLAND IN 2013-2020

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ABSTRACT: This paper investigates the relation between the prices of CO_2 emission allowances in the EU ETS (Emission Trading System) and wholesale prices of electricity in Poland. Linear regression models were used to assess carbon price pass-through rate to wholesale electricity prices during the entire III phase of ETS (2013-2020). It has been found that the entire cost of CO_2 emission allowances was included in the wholesale electricity price. As expected, the peak transmission parameter is higher than the off-peak one. Nevertheless, the difference is small and statistically insignificant. Hence the model does not allow for any far-reaching conclusions in this regard. Results show that electricity producers were able to pass the entire emission-related costs to the customers, which might raise a question of whether EU ETS is an effective tool to give sufficient incentives to decarbonise electricity production.

KEYWORDS: carbon price pass-through, electricity prices, CO_2 prices, emission Trading System

Introduction

Emission Trading System

Emission Trading System, established in 2005, is the main tool of EU climate policy, aiming at decarbonisation of the given sectors of the economy, i.a. electricity production. It is a so-called cap-and-trade system, where a fixed volume of emissions is set, and participating companies need to cover their emissions with allowances. The total amount of the allowances in the system decreases over time, which (*ceteris paribus*) leads to an increase in their price. This, in turn, should give obliged entities an incentive to reduce emissions, as then they would need to buy fewer allowances or could sell their possessed allowances on the market.

The cost of CO_2 emission allowances is an additional production cost for electricity producers, and its amount depends on the price of carbon credits, which varies over time and on the technology of energy production, which determines the level of emissions.

Transferring the emission costs to end consumers

The producers may partially or fully transfer the additional production costs to energy consumers. From the point of view of the system objective, which is reducing greenhouse gas emissions, it is important to determine what part of this additional cost is borne by the purchasers. That is because if energy producers can transfer all or most of the cost of CO_2 emissions to the consumers, then they have no incentives to invest in low-emission technologies, and thus the goal of ETS implementation is not achieved in the intended way. It can be partially achieved, as the increase in prices will cause a decrease in demand, therefore also a decrease in emissions. On the other hand, if producers fail to transfer a significant part of the costs to their consumers, they should be motivated to reduce emissions by investing in low or zero-emission technologies.

The issue under study has become particularly important in recent times, when we can observe an unprecedented increase in the prices of CO_2 emission allowances – over 500%, during the examined period: 2013-2020. This creates significant pressure on energy prices, and thus reduces the competitiveness of the economy, acts as an inflationary incentive, and causes impoverishment of the society and increase of inequality, as the poorer spend a proportionally larger part of their income on energy than the wealthier. The effects of this phenomenon will, of course, depend on i.a. on the emissivity of the energy mix of a given country. The more fossil-based generation sources, the higher the costs associated with participating in the ETS system.

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The problem is particularly acute in Poland, where sources based on coal, which is the most emissive fuel, have a significant share in the production structure.

So far, the issue of transferring the CO_2 costs to electricity prices, the so-called CO_2 cost pass-through rate – PTR, has been tested many times, but most of the studies concerned the first phases of ETS implementation when firstly, allowances were relatively cheap, and secondly, a significant part of them was allocated free of charge, thus they formed an opportunity cost, not a real cost (Sijm et al., 2005). Additionally, most of these studies did not cover Poland. This article is the first empirical study to cover the relation between the prices of emission allowances and electricity prices in Poland during the entire third phase of the ETS.

Determining the transfer of emission costs to electricity prices

In the theoretical analysis of the conditions influencing the level of transferring the costs of emissions to energy end consumers (CO_2 cost pass-through rate), the following are stated to be the key factors:

- the number of companies on the market, determining the level of competition,
- the shape of the demand curve (linear or iso-elastic),
- the shape of the supply curve (fixed costs before the ETS – perfect flexibility, horizontal curve, or variable costs before the ETS – positive slope).

Moreover, the following are also important (Sijm et al., 2005):

- company strategies (assumption can be profit maximisation, but sometimes, it can also be the maximisation of market share or a non-financial goal, e.g. ensuring energy security if it was a state-controlled company),
- market regulations (e.g. the method of allocating allowances),
- the possibility of demand-side response (e.g. switching from electricity to fuels),
- market failures (imperfect information, the need to maintain the continuity of power plant operation, costs of switching on/off, lack of liquidity in fuel markets),
- technological innovations in the field of emission reduction.

Additionally, the carbon intensity of marginal generation technology is a crucial factor in determining the carbon cost of electricity and influencing the pass-through rate. It depends on the fuel used and the thermal efficiency of the given technology. Marginal generation technology might change during peak and off-peak periods resulting in changes of carbon costs.

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Characteristics of the Polish electricity sector in 2013-2020

Polish energy system was historically dominated by fossil-based generation sources, with the dominant role of hard coal and lignite. During the entire III phase of ETS, we could observe a gradual transition from coal-based sources to renewable and gas-based generation. According to data from the transmission system operator (Polskie Sieci Elektroenergetyczne S.A.) structure of electricity generation by dominant sources in 2020 was as follows: hard coal – 47%, down from 52% in 2013, lignite – 24.9%, down from 35% in 2013, renewable energy sources – 10.7%, up from 3.6% in 2013, gas – 9.1%, up from 1.9% in 2013.

Indicated above transformation resulted in an overall decrease in emissivity of the polish energy sector from 150 mln tons of CO_2 equivalent in 2013 to about 124 mln tons of CO_2 equivalent in 2020. Despite the significant drop in emissivity, the Polish energy generation system remains one of the most emissive in the entire EU.

In 2013, the installed capacity in the National Power System was 38 406 MW and has increased to 49 238 MW in 2020. Installed capacity in 2020 by main generation sources was as follows: hard coal – 24.3 GW, lignite – 8.5 GW, renewables – 12.3 GW, gas and hydro – 4.1 GW. Among renewable energy sources, the largest share has an on-shore wind – 6.3 GW and PV – 4 GW.

Gross domestic electricity consumption in 2013 was 158.0 GWh and increased to 165.5 GWh in 2020. From a net exporter of electricity in 2013 – 4.5 TWh, Poland turned into a net importer – of 13.3 TWh in 2020. The increase in imports contributed to some extent to the reduction of GHG emissions from the energy sector.

The most important market for electricity trading is Polish Power Exchange (Towarowa Giełda Energii S.A. – TGE). The total volume of transactions concluded on all electricity markets at TGE S.A. was 176.5 TWh in 2013 and has increased to 243.2 TWh in 2020. The most liquid were one-year contracts.

According to the data of the president of the Energy Regulatory Office, the market share ratio of the three largest electricity producers, measured according to the energy dispatched into the grid (taking into account the amount of energy supplied by producers directly to end users), remained at a high level throughout the duration of the third phase of the ETS and accounted for 62.6% in 2013 and 63.8% in 2020.

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An overview of the literature

The issue of transferring the costs of carbon credits by electricity producers to end consumers was undertaken by many researchers. However, most of the studies concerned the early stages of the ETS implementation and focused on much shorter periods. Important papers in this area include the studies by Sjim (Sijm et al., 2005; Sijm et al., 2006). In the first study, the authors examined the degree of transferring emission allowance prices to energy prices in Germany and the Netherlands in the period of January – July 2005 using the OLS and PW regression method. The obtained results indicate that the coefficients of transferring costs to energy consumers in Germany were 0.72 (OLS), 0.69 (PW) for the PEAK period, and 0.42 (OLS and PW) for the OFF-PEAK period. In both cases, the marginal production technology was coal. In the Netherlands, the coefficients were 0.40 (OLS) and 0.44 (PW) in the PEAK period, where natural gas was considered as the marginal production technology, and 0.53 (OLS) and 0.47 (PW) for the OFF-PEAK, marginal technology – coal. In the second study, the authors investigated the transfer of carbon credit costs to energy prices in Germany and the Netherlands in the period of January – December 2005, using the linear regression method, estimating the parameter through the OLS method. The interesting thing is the fact that the results differed from the first study, covering the first half of 2005. The coefficients in Germany amounted to 1.17 in the PEAK period and 0.60 in the OFF-PEAK period, while in the Netherlands, they were 0.78 in the PEAK period and 0.80 in the OFF-PEAK period. For the PEAK period in the Netherlands, natural gas was adopted as the marginal source of production and for the remaining estimates – coal. A possible explanation given by the authors for the surprisingly high result for the PEAK period in Germany is a significant increase in gas prices in the examined period and the fact that gas could have been the marginal source of production in part of the PEAK period. The authors also refer to the significant differences between the coefficients for the first half of 2005 and the entire 2005, pointing to rising gas prices and delays in including the prices of emission allowances in energy prices as possible causes.

Jouvet and Solier (2013) examined the relations between the prices of CO_2 emission allowances and electricity prices in the period from June 2005 to April 2011 for selected EU countries: Germany, France, the Netherlands, Great Britain, Italy, Spain, and Nord Pool region (Sweden, Finland, Denmark, Norway), Poland, the Czech Republic and Austria. The authors conclude that in the first phase of the ETS, the impact of CO_2 emission allowance prices on energy prices was clearly visible, while in the second phase, it was not so evident. They explain it with the consequences of the economic crisis, result-

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ing in a decrease in demand for electricity, which in turn resulted in the lack of the possibility to transfer additional costs to consumers. In all cases, the emission cost pass-through coefficient was higher for the PEAK period than for the OFF-PEAK period, which, in the author's opinion, indicates a positive relationship between energy demand (energy consumption) and the transfer of CO_2 emission costs to consumers. At the same time, the R^2 coefficients indicate that the cost of carbon credits in the OFF-PEAK periods explains a greater part of the energy price variability than in the PEAK periods. As an explanation, the authors suggest production capacity shortages as an important element of price increases in the PEAK period. At the same time, only 42% of the pass-through rate coefficients turned out to be statistically significant, and 33% were statistically different from zero. The estimation of the parameter (the so-called pass-through rate) for Poland in the first phase of the ETS was 0.03 for the PEAK period and 0.1 for the OFF-PEAK period. However, in the second phase of the ETS, the estimates were 0.41 for the PEAK period and –0.35 for the off-peak period.

The issue of transferring the costs of CO_2 to electricity prices is also discussed by Pereira Freitas and Pereira da Silva (2015). The study covers the entire second phase and first year of the third phase of the EU ETS, i.e. from January 2008 to December 2013. The Vector Error Correction model was used. The authors, just like Jouvet and Solier (2013), note the weakening of the relation between the prices of emission allowances and the prices of electricity as a result of a marked decline in the records of the first ones resulting from the economic crisis. Estimated parameters amounted to 0.24 for the PEAK and OFF-PEAK periods and 0.25 for the BASE period.

Castagneto-Gissey (2014) investigated the relationship between the prices of emission allowances and the electricity prices in Germany, France, Great Britain and the Nord Pool region, using the VAR and GARCH models. The study used data from futures contracts expiring at the end of a given year, and the model takes into account such variables as the price of fuel (coal and natural gas). The results presented high values of the coefficient indicating the emission cost pass-through to electricity prices and amounted to 1.35 in Germany, 0.88 in France, 1.09 in Great Britain, and 1.37 for Nord Pool, which means that producers increased energy prices more than it would result from the cost of carbon credits in 3 of the above cases. The author speculates that transferring so much of the cost of CO_2 might suggest a lack of perfect competition in electricity markets.

The issue of transferring carbon costs to energy prices in markets where there is no perfect competition was examined by Chernyavs'ka and Gulli (2008). The authors focus on the Italian market, which is marked by a high concentration in the power generation sector. They conclude that depending on structural factors, such as the level of concentration on the power genera-

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tion market or the availability of generation capacity, the increase in energy prices may be higher or lower than the marginal cost of CO_2 emission allowances. In addition, the important factor is the level of demand, i.e. only a part of the marginal cost is transferred to energy consumers in the PEAK period, while in the OFF-PEAK period, the price includes all of this cost or even more.

Bonacina and Gulli (2007) analysed the theoretical, short-term impact of emission allowance prices on electricity prices. According to the research, CO_2 prices are completely transferred to energy prices if there is perfect competition in the market. In the situation of imperfect competition, the impact of allowance prices is higher than in the case of perfect competition only when the share of the most emitting sources is small, and there are generation overcapacities. In other situations, especially in the case of the absence of generation overcapacity, the impact of emission allowance prices on energy prices is smaller in the case of imperfect-than-perfect competition. Additionally, in the case of imperfect competition in the PEAK periods, producers transfer less than 100% of CO_2 costs to energy prices, at the same time, this ratio may be lower than in the OFF-PEAK periods.

The panel dataset, including data for 24 thermal power plants, was used by Dagoumas and Polemis (2020) to investigate carbon pass-through in the Greek electricity sector in the period from January 2014 to December 2017. Results showed very significant pass-through of the CO_2 permit costs to end-costumers, as the pass-through rate ranges from 0.639 to 1.196.

Impact of the EU emission trading system on the Nordic electricity market and on different market actors was investigated by Kara (Kara et al., 2008). The period under examination covered the first phase of ETS. The main finding was that for every tonne of $CO_{2,}$ the annual average electricity price rise by 0,74 EUR/MWh.

Huisman and Kilic (2015) found support for the time-varying of pass-through rate by applying a Kalman Filter approach. The study focused on future prices in UK and Germany. The main conclusion from the study is that pass-through might not be constant over time.

There are also examples of studies investigating CO_2 cost pass-through from non-EU cap and trade systems, e.g. in California (Woo et al., 2017). The period from January 2011 to December 2016 was investigated. Results showed, depending on the particular market, an increase in electricity prices by 0.41 US$/MWh and 0.59 US$/MWh, for each 1 US$ increase in a tonne of CO_2 price.

An investigation concerning the influence of the emission permit allocation method on the CO_2 pass-through rate was conducted by Wang and Zhou (2017). Nash-Cournot oligopolistic market equilibrium model was employed to find out that the allocation method does affect the rate of CO_2 cost pass-through.

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Research methods

This article presents the research results on the relation between the prices of CO_2 emission allowances and wholesale prices of electricity listed on the Polish Power Exchange (Towarowa Gielda Energii – TGE) in Warsaw. The research period covers the entire 3rd phase of the ETS (2013-2020).

The study covers three daily supply periods characteristic of the energy market, reflected by three different contracts listed on the TGE:

- BASE – 24h energy delivery reflects the average daily energy demand,
- PEAK – deliveries in the so-called peak period, i.e. between 7:00 a.m. and 10:00 p.m., when the demand for energy is the highest,
- OFF-PEAK – deliveries in the off-peak period, i.e. between 10:00 p.m. and 7:00 a.m., when the energy demand is the lowest.

Based on the data from the above types of contracts, three linear regression models were estimated.

Data

Average monthly prices of electricity, hard coal and CO_2 emission allowances from the analysed period were used for the study, which gives the sample size N = 96 (12 months x 8 years in the period of 2013-2020). For each of the examined periods, the average monthly price of electricity from the contract corresponding to the given period of the day (BASE, PEAK, OFF-PEAK), reported by TGE S.A. (operator of the Commodity Power Exchange), was used. Therefore, the sample consisted of N = 96 observations for each of the three estimated models.

Model

In order to find out what part of the cost of carbon allowances was transferred to end customers of energy in Poland in 2013-2020, the following models were estimated:

$$Yt = (Pt - Ft) = \alpha + \beta 1 \cdot CO_2 + \xi \quad (1)$$

where:
Pt – energy price for [MWh],
Ft – hard coal price [MWh],
CO_2 – price of emission allowances,
Yt (Pt – Ft) – dark spread – the price of energy minus the price of fuel, in other words, the price of energy “cleared” by the price of fuel.

The coal price has been converted into MWh and corrected by the average energy efficiency of coal power plants (assuming 0.4).

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CO_2 emission allowance price was corrected by the emissivity of coal power plants (assuming 0.8). Example: the production of 1 MWh of energy emits 800 kg of CO_2, therefore, if the CO_2 emission allowance costs, e.g. EUR 25, then the additional cost of producing 1 MWh of energy in a coal power plant is EUR 20.

The β_1 parameter is the so-called CO_2 cost pass-through rate – which shows part of the costs that are transferred by producers to customers. For example, if it is 0.8, it will mean that producers transfer 80% of the cost of allowances to electricity prices.

The marginal generation unit determines the price of energy on the market. In the Polish power system, it is a hard coal power plant in each period of the day, hence the analysis assumed the energy efficiency and emissivity of such units.

Hypotheses

The research hypothesis assumes that the parameter will be positive ($\beta_1 > 0$) and that it will be statistically significant – it means that the costs of emission allowances were transferred to end customers in the analysed period. Taking into account the structure of electricity generation sources in Poland, it should be expected that the parameter will be close to 1.

An additional hypothesis assumes that the β_1 coefficient will be higher in those periods of the day when the demand for energy is higher (producers have greater bargaining power) and lower in periods of relatively lower demand. In other words, the largest part of the emission allowance cost is transferred by producers to customers between 7.00 a.m. and 10.00 p.m. (PEAK contract) and the least between 10.00 p.m. and 7.00 a.m. (OFF-PEAK contract), ($\beta_{PEAK} > \beta_{OFF\text{-}PEAK}$). Statistical test of the hypothesis: $\beta_{PEAK} = \beta_{OFF\text{-}PEAK}$ was conducted to investigate this.

Results of the research

In the models estimated with the OLS method, there was an autocorrelation of the residuals. Therefore, the models were estimated using the Cochrane – Orcutt method. Detailed model estimation and tables of diagnostic test results are provided in the appendix.

Parameters β_1 next to the CO_2 prices variable turned out to be statistically significant at the level of 0.01 in all examined periods, which confirms the main hypothesis of the study.

- BASE period – the parameter $\beta_{BASE} = 0.996$ and the coefficient $R^2 = 0.78$.

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- PEAK period – the parameter $\beta_{PEAK} = 1.011$ and the coefficient $R^2 = 0.70$.
- OFF-PEAK period – parameter $\beta_{OFF\text{-}PEAK} = 0.979$ and the coefficient $R^2 = 0.92$.

Regarding the second hypothesis, the results suggest that during the peak demand period, the cost of energy increases by 1.1% more than it would be presumed from the cost of CO_2 emission allowances. During the off-peak period, a bit less than the entire cost of carbon is passed through, namely 98% of it. As expected, the peak transmission parameter is higher than the off-peak one. Nevertheless, the difference is small and statistically insignificant. Hence the model does not allow for any far-reaching conclusions. P-value for the tested hypothesis is 0.1577.

Table 1. Results of the research – BASE, PEAK, OFF-PEAK periods, 2013-2020

	β	R^2
BASE	0.996	0.78
PEAK	1.011	0.70
OFF-PEAK	0.979	0.92

Discussion/ Limitation and future research

Most of the studies on CO_2 cost pass-through rate have revealed that carbon price impacts electricity price leading to its increase. However, the pass-through rate values estimated in previous studies differ significantly. Depending on the country and period studied, the researchers obtained pass-through rate results both significantly lower than 1 (suggesting only a small inclusion of emission costs in electricity prices) and significantly higher than 1 (suggesting the opposite).

The results of the CO_2 cost pass-through rate from this paper are different from those obtained by Jouvet and Solier for the polish electricity market. However, it should be noted that the period investigated was different, and so were CO_2 allowance prices.

On the other hand, in this paper, likewise in Jouvet and Solier study (2013), CO_2 pass-through rate was higher in PEAK period, when demand was higher, as well as R^2 coefficient was lower for PEAK period indicating that carbon cost in OFF-PEAK period explains a greater part of variability of electricity prices, than in BASE and PEAK periods, when other factors might also play significant role.

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Due to the importance of the problem of relation between the prices of CO_2 emission allowances and electricity prices, this issue is worth carrying out further research, especially since the changing structure of generation, new technologies, but also higher prices of allowances may affect the situation in relation to the analysed period.

Conclusions

The conducted study confirmed that electricity producers in Poland transferred virtually the entire additional cost of CO_2 emission on the wholesale electricity price during III ETS phase (2013-2020). In the periods of the greatest demand, the price was even higher than it would appear from the cost of allowances, but it can be assumed that producers could thus compensate for periods of lower demand, when they were not able to transfer all costs on electricity prices. Nevertheless, the difference is small and statistically insignificant, hence the model does not allow for any far-reaching conclusions in this regard.

The research problem is important because the policy of the European Union assumes more and more ambitious goals of reducing greenhouse gas emissions and one of the main tools for its implementation will be the ETS system. Therefore, further increases in the prices of CO_2 emission allowances should be expected. In 2021, the so-called 4th phase of the ETS implementation went into effect, under which i. a. the reduction of the number of allowances in the system has been accelerated. From January to December 2021, the price of allowances increased from about 25 EUR/t to over 80 EUR/t, which puts significant pressure on the increase in electricity prices. The effects will be felt both in the economic sphere (less competitiveness of industry in the EU) and in the social sphere (increasing burden, especially for the poorer part of the society). The most problematic issue occurs in countries like Poland, where most of the electricity is still produced from coal.

If electricity producers transfer the entire cost of allowances to electricity prices, questions may arise both about the effectiveness of the ETS – based policy (what are the incentives to reduce emissions) and about who eventually bears the costs of the energy transformation.

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Appendix A

A.1 Model 1 – price in BASE contracts

Model estimation using the OLS method

OLS estimation, observations used 2013:01-2020:12 (N = 96)

Dependent variable (Y): seasonally adjusted_energy_prices_Y

	Coefficient	standard error	Student's t-distribution	p-value
Const	140.335	4.37801	32.05	2.13e-052 ***
CO_2_prices	0.920399	0.123822	7.433	4.84e-011 ***

Average of dependent variable 177.9228 Standard deviations of dependent variable 34.59021

Sum of squares of residuals 43198.47 Standard error of residuals 21.43731

Determination coefficient R-squared 0.619952 Adjusted R-squared 0.615909

F(1, 94) 55.25272 p-value for the test F 4.84e-11

Logarithm of likelihood −429.4603 Akaike information criterion 862,9206

Bayesian information criterion 868.0493 Hannan-Quinn criterion 864.9937

Autocorrelation of residuals – rho1 0.648682 Durbin-Watson statistic 0.707029

Model estimation using the Cochrane-Orcutt method

Cochrane-Orcutt estimation, observations used 2013:02-2020:12 (N = 95)

Dependent variable (Y): seasonally adjusted_energy_prices

rho = 0.65227

	coefficient	standard error	Student's t-distribution	p-value
const	137.392	8.11901	16.92	3.84e-030 ***
season.adjusted_CO_2_prices	0.996712	0.151589	6.575	2.80e-09 ***

Basic statistics for quasi-differentiated data (rho):

Sum of squares of residuals 25249.08 Standard error of residuals 16.47712

Determination coefficient R-squared 0.777716 Adjusted R-squared 0.775325

F(1, 93) 43.23181 p-value for test F 2.80e-09

Autocorrelation of residuals – rho1 −0.134289 Durbin-Watson statistic 2.238513

Basic statistics for original data:

Average of dependent variable 178.0699 Standard deviation of dependent variable 34.74355

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OLS method				
No.	**TEST**	**H:0**	**Statistics**	**p-value**
1.	Y variable stationarity (ADF test)	There is a unit root	tau_nc(1) = 0.651253	p = 0.8568
	X variable stationarity (ADF test)	There is a unit root	tau_nc(1) = 2.63412	P = 0.9979
	Stationarity of cointegrating equation residuals (ADF test)	There is a unit root	tau_nc(1) = -2.58612	p = 0.00941
2.	Distribution normality (J-B test)	the distribution is normal	2.31999	0.313488
3.	Model linearity (RESET test)	correct specification	F = 3.249527	p = P(F(2, 92) > 3.24953) = 0.0432878
4.	Parameter stability (CUSUM test)	no change in parameters	t(93) = -4.43198	p = P(t(93) > -4.43198) = 2.55044e-005
5.	ARCH effect (instead of heteroscedasticity test)	ARCH effect does not occur	LM = 18.741	p = P(Chi-square(12)> 18.741) = 0.0949745
6.	Autocorrelation (Durbin – Watson test)	No autocorrelation AR(1)	0.707029	p = 1.05118e-013
7.	Autocorrelation (Breusch – Godfrey test)	No autocorrelation AR(p)	LMF = 65.286405	p = P(F(1, 93) > 65.2864) = 2.31e-012
Cochrane-Orcutt method				
No.	**TEST**	**H:0**	**Statistics**	**p-value**
1.	Residual distribution normality test	random component is normally distributed	Chi-squared(2) = 14.0534	p = 0.000887837
2.	ARCH test	ARCH effect does not occur	LM = 13.009	p = P(Chi-squared(1) > 13.009) = 0.000310006

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A.2 Model 2 – price in PEAK contracts

Model estimation using the OLS method

OLS estimation, observations used 2013:01-2020:12 (N = 96)

Dependent variable (Y): seasonally adjusted_energy_prices_Y

	Coefficient	Standard error	t-Student's	p-value	
Constant	158.378	5.91642	26.77	<0.0001	***
CO_2_prices	0.918120	0.147680	6.217	<0.0001	***

Arithmetic mean of the dependent variable	195.8726		Standard deviation of the dependent variable	38.18703
Sum of squares of residuals	68.414.88		Standard error of residuals	26.97810
Determination coefficient R-squared	0.506150		Adjusted R-squared	0.500896
F(1.94)	38.65043		P-value for the F test	1.38e-08
Logarithm of likelihood	−451.5300		Akaike information criterion	907.0599
Bayesian information criterion	912.1886		Hannan-Quinn criterion	909.1331
Autocorrelation of residuals – rho1	0.626098		Durbin-Watson statistic	0.752990

Model estimation using the Cochrane-Orcutt method

Cochrane-Orcutt estimation, observations used 2013:02-2020:12 (N = 95)

Dependent variable (Y): seasonally_adjusted_energy_prices_Y

rho = 0.630521

coefficient standard error Student's t-distribution p-value

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const	154.972	9.89310	15.66	7.97e-028 ***
CO_2_prices	1.01193	0.185773	5.447	4.16e-07 ***

Basic statistics for quasi-differentiated data (rho):

Sum of squares of residuals 42033.34 Standard error of residuals 21.25962

Determination coefficient R-squared 0.696055 Adjusted R-squared 0.692787

F(1, 93) 29.67148 p-value for test F 4.16e-07

Autocorrelation of residuals – rho1 −0.128615 Durbin-Watson statistic 2.223444

Basic statistics for original data:

Mean of dependent variables 196.0782 Standard deviation of dependent variables 38.33617

OLS method				
No.	**TEST**	**H:0**	**Statistics**	**p-value**
1.	Y variable stationarity (ADF test)	There is a unit root	tau_c(1) = -1.81342	p = 0.3744
	X variable stationarity (ADF test)	There is a unit root	tau_c(1) = 1.14953	p = 0.9977
	Stationarity of cointegrating equation residuals (ADF test)	There is a unit root	tau_nc(1) = -3.32311	p = 0.0008714
2.	Distribution normality (J-B Test)	the distribution is normal	12.0424	0.00242677
3.	Model linearity (RESET test)	correct specification	F(2, 92) = 4.07519	p = P(F(2, 92) > 4.07519) = 0.0201475
4.	Parameter stability (CUSUM test)	no change in parameters	t(93) = -4.04387	P(t(93) > -4.04387) = 0.000108398
5.	ARCH effect (instead of heteroscedasticity test)	ARCH effect does not occur	LM = 4.59527	P(Chi-squared(1) > 4.59527) = 0.0320604
6.	Autocorrelation (Durbin – Watson test)	No autocorrelation AR(1)	0.75299	p = 1.21803e-012
7.	Autocorrelation (Breusch – Godfrey test)	No autocorrelation AR(p)	LMF = 57.971267	P(F(1, 93) > 57.9713) = 2.15e-011
Cochrane-Orcutt method				
No.	**TEST**	**H:0**	**Statistics**	**p-value**
1.	Residual distribution normality test	random component is normally distributed	Chi-squared(2) = 21.0082	p = 2.74235e-005
2.	ARCH test	ARCH effect does not occur	LM = 10.5461	P(Chi-squared(1) > 10.5461) = 0.00116431

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A.3 Model 3 – price in OFF-PEAK contracts

Model estimation using the OLS method

OLS estimation, observations used 2013:01-2020:12 (N = 96)

Dependent variable (Y): seasonally adjusted_energy_prices_Y

	Coefficient	Standard error	t-Student's	p-value	
constant	106.816	2.64355	40.41	<0.0001	***
CO_2_prices	0.922084	0.0936285	9.848	<0.0001	***

Arithmetic mean of the dependent variable	144.4723		Standard deviation of the dependent variable	30.44283
Sum of squares of residuals	17317.17		Standard error of residuals	13.57296
Determination coefficient R-squared	0.803310		Adjusted R-squared	0.801217
F(1, 94)	96.98940		P-value for the F test	3.86e-16
Logarithm of likelihood	−385.5832		Akaike information criterion	775.1663
Bayesian information criterion	780.2950		Hannan-Quinn criterion	777.2394
Autocorrelation of residuals – rho1	0.767498		Durbin-Watson statistic	0.445817

Model estimation using the Cochrane-Orcutt method

Cochrane-Orcutt estimation, observations used 2013:02-2020:12 (N = 95)

Dependent variable (Y): seasonally_adjusted_energy_prices_Y

rho = 0.768605

coefficient standard error Student's t-distribution p-value

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const	103.758	6.10284	17.00	2.76e-030 ***
CO_2_prices	0.979490	0.108141	9.058	2.02e-014 ***

Basic statistics for quasi-differentiated data (rho):

Sum of squares of residuals 6769.239 Standard error of residuals 8.531560

Determination coefficient R-squared 0.923211 Adjusted R-squared 0.922385

F(1, 93) 82.03833 p-value for test F 2.02e-14

Autocorrelation of residuals – rho1 −0.100339 Durbin-Watson statistic 2.185654

Basic statistics for original data:

Average of dependent variable 144.4970 Standard deviation of dependent variable 30.60336

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OLS method				
No.	**TEST**	**H:0**	**statistics**	**p-value**
1.	Y variable stationarity (ADF test)	There is a unit root	tau_c(1) = -0.66652	p = 0.8492
	X variable stationarity (ADF test)	There is a unit root	tau_c(1) = 1.14953	p = 0.9977
	Stationarity of cointe-grating equation residu-als (ADF test)	There is a unit root	tau_nc(1) = -3.58635	p = 0.0004572
2.	Distribution normality (J-B Test)	the distribution is normal	16.5513	0.000254642
3.	Model linearity (RESET test)	correct specification	F(2, 92) = 0.394645	p = P(F(2, 92) > 0.394645) = 0.675055
4.	Parameter stability (CUSUM test)	no change in parameters	t(93) = -3.69424	P(t(93) > -3.69424) = 0.000372193
5.	ARCH effect (instead of heteroscedasticity test)	ARCH effect does not occur	LM = 34.8987	(Chi-squared(1) > 34.8987) = 3.47305e-009
6.	Autocorrelation (Durbin – Watson test)	No autocorrelation AR(1)	0.445817	p = 0
7.	Autocorrelation (Breusch – Godfrey test)	No autocorrelation AR(p)	LMF = 130.972193	P(F(1, 93) > 130.972) = 1.91e-019
Cochrane-Orcutt method				
No.	**TEST**	**H:0**	**Statistics**	**p-value**
1.	Residual distribution normality test	random component is normally distributed	Chi-squared(2) = 6.53677	p = 0.0380678
2.	ARCH test	ARCH effect does not occur	LM = 1.90805	P(Chi-squared(1) > 1.90805) = 0.167179

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Appendix B

Data statistics

Table 1. Descriptive statistics for observations from the sample 2013:01 – 2020:12 for the energy_price_Y variable for the BASE period (96 correct observations)

Average	Median	Minimum	Maximum
178.12	163.06	131.88	268.34
Standard deviation	Variation coefficient	Skewness	Kurtosis
37.179	0.20873	0.75673	-0.73304
Percentile 5%	Percentile 95%	Range Q3-Q1	Missing observations
134.81	248.08	61.181	0

Table 2. Descriptive statistics for observations from the sample 2013:01 – 2020:12 for the energy_price_Y variable for the PEAK period (96 correct observations)

Average	Median	Minimum	Maximum
196.18	181.71	144.10	302.98
Standard deviation	Variation coefficient	Skewness	Kurtosis
40.880	0.20838	0.69531	-0.71489
Percentile 5%	Percentile 95%	Range Q3-Q1	Missing observations
148.30	272.11	68.555	0

Table 3. Descriptive statistics for observations from the sample 2013:01 – 2020:12 for the energy_price_Y variable for the OFF-PEAK period (96 correct observations)

Average	Median	Minimum	Maximum
144.84	130.67	105.03	233.20
Standard deviation	Variation coefficient	Skewness	Kurtosis
33.254	0.22959	1.0021	-0.41275
Percentile 5%	Percentile 95%	Range Q3-Q1	Missing observations
111.00	210.22	48.033	0

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Table 4. Descriptive statistics for the observations from the sample 2013:01 – 2020:12 for the CO_2 emission allowance_prices_X variable (96 correct observations). The price of CO_2 emission allowances is the same for each model

Average	Median	Minimum	Maximum
40.907	24.097	11.838	110.49
Standard deviation	Variation coefficient	Skewness	Kurtosis
29.845	0.72959	0.83948	-0.96281
Percentile 5%	Percentile 95%	Range Q3-Q1	Missing observations
14.595	95.250	54.636	0

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