CARBON FUEL SOURCES AND ELECTRICITY PRICES IN EUROPE: WHY U.S. ENERGY MARKET POLICIES MATTER

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Overview

The largely unexpected boom in U.S. unconventional oil and natural gas production has been one of the most important energy market shocks in recent decades. It has led low domestic U.S. natural gas prices decoupled from their historic relationship to the crude oil market (Erdős, 2012, Oglend et al, 2015). However, because of regulatory and export capacity constraints, the major of the direct effects of the boom have been localized to the domestic U.S. energy market. For instance, it is difficult to identify much of an impact on European natural gas prices, which maintained stable high levels during the earlier period of the shale gas boom (2009-2014). Furthermore, Asian LNG prices have continued to trade at a substantial premium to U.S. natural gas (Oglend, et al 2016,2020).

The purpose of this paper is to document an important and policy relevant indirect channel by which the recent U.S. energy boom has affected European energy markets. Specifically, we argue that cheaper U.S. natural gas has contributed to lower electricity price in Europe. The channel here is cheaper imported U.S. coal. Natural gas and coal are substitutes in electricity generation, and cheap U.S. natural gas has led to lower demand for coal in U.S. electricity generation. This has kept down the price of U.S. coal (Basher, 2019). Furthermore, contrary to crude oil and natural gas, U.S. coal exports have faced no major export restrictions, and since Europe is one of the main export market for U.S. coal (second behind India in 2018, https://www.eia.gov/tools/faqs/faq.php?id=66&t=2), this has led to cheaper coal in Europe. With coal remaining a marginal supplier of electricity in Europe, this has contributed to lower electricity prices.

We make this case empirically. By using conventional time-series analysis we show that the Nord-Pool electricity price trend from 2008 to 2019 was influenced by the trend in the North-West Europe (NWE) coal price, consistent with previous studies in Europe (Frydenberg et al, 2014) and the U.S. (Mohammadi, 2009). The empirical analysis controls for the expansion in renewables generation in the period, as well as the impact of other carbon fuel sources (U.K. natural gas and Brent crude oil). As in Lion (2018), we find that expansion in renewables capacity has been important for the Nord-Pool electricity market in the period, providing a price impact like that of access to cheaper coal. After documenting that the NWE coal price has influenced the trend in the Nord-Pool electricity price, we show that the NWE coal price trend itself can be explained the unique U.S. natural gas price trend that emerged as a result of the shale gas boom. We instrument the NWE coal price trend by the (weakly exogenous) U.S. natural gas price trend, and provide empirical evidence that the cheap U.S. natural gas can explain the price effect of coal on the Nord-Pool electricity price in the period.

Our findings have direct relevance to the effects of U.S. energy market conditions and policies European energy markets. It also speaks to the economics of continued renewables expansion in Europe. If coal remains an important marginal supplier in electricity generation, factors affecting coal will affect electricity prices. For instance, expanding U.S. export capacity and raising the price of U.S. natural gas will leave room for higher U.S. coal prices. While lower relative prices of coal might displace natural gas in domestic U.S. electricity generation, it will likely raise European coal prices, providing better conditions for renewables investments in Europe.

Methods

The impact of carbon fuel source prices and renewables capacity on the Nord-Pool electricity price is analysed using conventional econometric methods of analysing non-stationary time series. The long-run relationship between electricity and carbon fuel sources is analysed using cointegration methods. Following this we investigate Granger non-causality between using the Toda and Yamamoto method that is robust to the order of integration of the prices. The Granger non-causality analysis distinguishes between short-run and long-run causality according to the cointegration results.

We model the detailed dynamics of the electricity price using an Autoregressive Distributed Lag Model (ARDL). The ARDL adjusts for contemporaneous endogeneity by including contemporaneous differences of the independent variables. The conditional model is estimated in first difference form and includes both first differenced and level variables. This allows the use of the Pesaran and Shin (2001) bounds testing framework to test for significant level relationships. The bounds test is robust to regressors being either I(1) or I(0), and the ARDL model yields consistent estimates of long-run coefficients that are asymptotically normal. The downside of the ARDL model is that it treats regressors as dynamically exogenous. This ignores possible dynamic feedback effects from the regressand to the regressor when investigating dynamic adjustments of electricity prices to fuel source price shocks. However, the Granger non-causality analysis establishes that the electricity price is long-run non-causal such that the electricity prices will only affect short run movements in the regressands (oil and natural gas specifically).

The impact of shocks to carbon fuels source prices and renewables capacity on electricity prices is analysed using simulated impulse responses. This traces the dynamic impact of the shocks on the electricity price and provides a measure of the size of the effects.

Results

Before presenting and discussing the results of the empirical analysis, we provide some discussion and descriptive statistics of the data used in the analysis.

Data

We investigate pricing in the integrated Nord-Pool electricity market. The price used is the weekly average system price in USD/Mwh. from week 1 in 2008 to week 20 in 2019. As coal and crude oil is traded in USD, we convert all prices used in the analysis to USD. We use Crude Oil (Brent spot), Coal (North-West Europe Front Month Forward), and Natural Gas (NBP ICE day ahead price) prices to measure the prices of relevant carbon fuels sources used in electricity generation. To convert the carbon fuel source prices to a common price per Mwh. electricity generation unit we apply average power generation efficiency rates. Crude oil and coal generation assumes an efficiency rate of 37% (1 MWh crude oil or coal is converted to 0.37 MWh electricity), while natural-gas assumes an efficiency rate of 50%. This ensures all our prices are measured in a common USD per Mwh. electricity unit.

The sample period is characterized by a focus on and expansion in renewables capacity for electricity production. For the Nord-Pool market, wind power capacity has increased substantially over the period. Expansion in renewables capacity is likely to have had permanent effects on electricity prices. To control for this impact, we use data on weekly systemwide production of wind power and availability of hydro reserves. Quantity variables are used as price data on renewable fuel sources are not available. The renewables data is available from 2013. As such we analyse two sample periods, the full sample from 2008 to 2019 without renewables, and a sub-samples from 2013 to 2019 that includes the effects of renewables.

Finally, it is well known that temperatures strongly affect the electricity price. However, our primary concern is the trend in the electricity price, and temperature variations largely relates to short run volatility (i.e. price spikes), which is not of primary concern to our analysis.

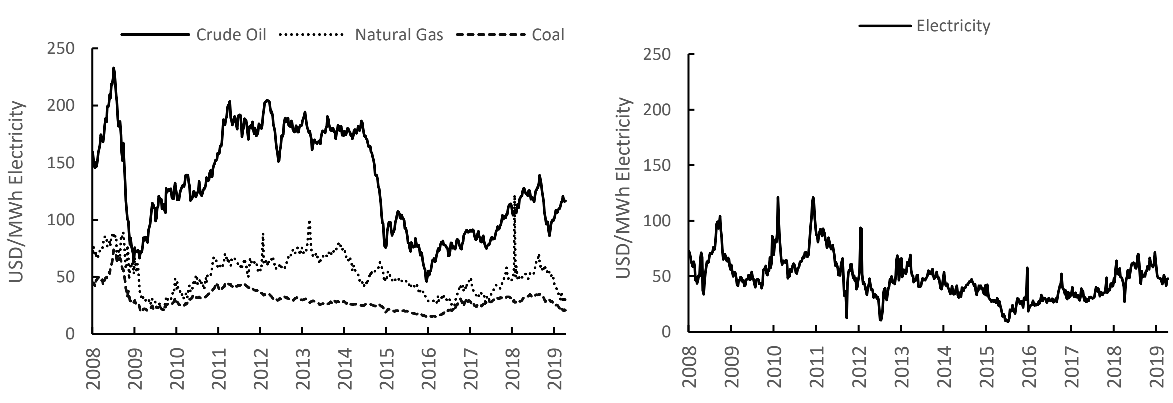

FIGURE 1. Direct Cost of Electricity Generation by Carbon Fuel Source (left), and the price of Electricity (right)

Figure 1 plots the prices of carbon fuels sources (left panel) and the Nord-Pool electricity price (right panel). Taken as direct price measures of operational costs in electricity generation, the carbon fuel prices show a clear ranking with crude oil as the costliest fuel source, followed by natural gas and then coal. Of course, prices do not contain carbon costs. The price data shows the strong effect of the Great recession (2008-2009) and the swift recovery of the oil price until the major decline in the fall of 2014. Natural gas and coal show a similar relative decline. However, coal did not recover to the same degree as crude oil, having a clear negative trend from 2011 to 2016. Natural gas continued increasing after its low in 2009, diverging from coal up until 2014. The electricity price did not display a substantial decline and recovery pattern following the great recession. Prices peaked around 2011 and after that declined until 2015 when it started increasing.

Table 1 presents test results for the null of a unit-root (non-stationarity, ADF and DF-GLS tests) and stationarity (KPSS) carbon fuel source prices in levels and first differences. All tests agree that crude oil and coal contains a stochastic trend but are stationariy in first differences. The ADF tests for the null of a unit root is inconclusive for U.K. natural gas, while the Elliott, Rothenberg & Stock (1995) test with local detrending (ERS) and KPSS test suggests a stochastic trend and stationarity in first differences. A similar borderline result is found for electricity. As is reasonable, there is less evidence of a strong stochastic trend in the non-storable electricity price. Natural-gas and electricity contains larger short-run run price volatility relative to the more persistent coal and crude oil prices.

TABLE 1. Unit-root and Stationary Properties of European Market Carbon Fuel Sources and Electricity

	ADF	ERS (DF-GLS)	KPSS
Brent Oil	-1.631	-1.754	0.996***
Δ Brent Oil	-14.42***	-6.609***	0.0541
U.K. Natural Gas	-2.931**	-1.086	0.541**
Δ U.K. Natural Gas	-20.51***	-9.603***	0.0567
NWE Coal	-2.099	-1.0573	0.957***
Δ NWE Coal	-13.73***	-8.219***	0.0393
Nord-Pool Electricity	-4.448***	-1.683*	1.266***
Δ Nord-Pool Electricity	-20.70***	-19.21***	0.0376

Note: Null for the Augmented Dickey Fuller (ADF) test is a unit-root process with drift, lag order selected by AIC. The ERS (DF-GLS) test is the Elliott, Rothenberg & Stock (1992) test with local detrending, detrended with constant. The KPSS test is the Kwiatkowski, Phillips, Schmidt and Shin (1992) test where the null hypothesis is stationarity (with constant. ***, **,* denotes rejection of the null hypothesis at 1%, 5% and 10% critical values respectively.

Nord-Pool Electricity Price Determination

We start the formal analysis of the Nord-Pool electricity price determination by investigating the Granger non-causality patterns between electricity and the carbon fuel sources. Rejecting Granger-non causality for price i in the equation determining price j implies that movements in price i is predictive of price j. A failure to reject does not imply that price j is fully exogenous with regards to price i, only that its future price movements are linearly unrelated to the history of price i. A full causal analysis would require modelling the instantaneous (within week) relationship between the prices, which is beyond the scope of this paper.

Testing for Granger non-causality is based on a bivariate VAR model of each carbon fuel source and the electricity price. We start by investigating the presence of a significant long-run relationship between the prices. This is done using the conventional Johansesn (1988) trace test for the rank of the cointegrating space. If a long-run relationship is detected, we distinguish between short-run and long-run Granger non-causality. Rejecting short-run Granger non-causality implies predictive power on weekly price changes. Rejecting long-run Granger non-causality implies predictive power on price trend. To control for the possibility of indeterminate orders of integration we also apply the general Toda and Yamamoto (1995) test for non-causality using a VAR in levels. Table 2 reports the Granger non-causality tests. The trace test statistics for significant long-run relationship is not displayed in the table but is available on request.

TABLE 2. p-values of Granger Non-causality Tests of Carbon fuels Sources and Nord-Pool electricity Price

H0	Long-Run	Short-Run	General
Brent does not Granger cause Nord Pool Electricity	-	0.762	0.605
Nord Pool Electricity does not Granger cause Brent	-	0.028	0.049

U.K. Natural Gas does not Granger cause Nord Pool Electricity	-	0.027	0.069
Nord Pool Electricity does not Granger cause U.K. Natural Gas	-	0.118	0.064
NWE Coal does not Granger cause Nord Pool Electricity	0.001	0.250	0.099
Nord Pool Electricity does not Granger cause NWE Coal	0.234	0.898	0.828

Note: Long-Run test is based on the evidence of co-integration, where we use a 5% critical value to determine whether co-integration is present. If co-integration is detected, we test for non-adjustment to cointegration errors. Short-run is a test for Granger non-causality in a VAR in differences. General is the Toda and Yamamoto (1995) test for non-causality using a VAR in levels with additional lag added based on the maximum order of integration of the data.

First, we note that only coal displayed a significant long-run trend relationship to the Nord-Pool electricity price. This implies that the Nord-Pool electricity price does not share a common trend with Brent crude oil and U.K. natural gas prices. This is consistent with coal operating as the marginal supplier in the electricity market such that its trend will affect the electricity price trend.

In terms of Granger non-causality, we find some evidence that the Nord-Pool electricity price has some predictive power on short run weekly changes in the crude oil price. We find no evidence that crude oil significantly affects electricity.

For natural-gas the evidence is strongest for natural-gas having short some run predictive power on electricity prices, but the effect is not strongly significant.

Coal has a significant long-run relationship with electricity, and the results imply that the trend in electricity price is determined by the coal price. That is, the coal price trend is a weakly exogenous driver of the Nord-Pool electricity price. Compared to natural gas and oil, the relationship between coal and electricity is a pure trend relationship, there is no evidence that weekly changes to coal or electricity prices have any predictive power.

The preliminary analysis suggests that the coal price trend has influences the Nord-Pool electricity price trend for the sample period. We next move to a more detailed analysis of the electricity price determination. To do so we model the electricity price using an ARDL model. The ARDL model is cast in an error-correction form where the dependent variable is the weekly change in the electricity price. The independent variables are the lagged and up to two weeks lagged first differences of the electricity, crude oil, natural gas and coal prices. To account for instantaneous correlations the non-electricity prices also contains the instantaneous first difference as independent variables. In the sample from 2013 to 2019 the model is augmented with the lagged level and first differences of Nord-Pool hydro reserve and wind power generation, all expressed in 10 000 Mwh.

To test for a significant long-run relationship we use the Pesaran, Shin, and Smith (2001) bounds test. This is a joint test that is robust to the order of integration of the data, (I(1) or I(0)). The F-test is a test for the joint null that the levels of the independent variables have no impact on the electricity price. The t-test is a single test for the null that the lagged level of the dependent variable is zero. Rejecting both nulls imply a significant long run relationship between the data in the model. Table 3 reports the full estimation results.

Results suggests that crude oil has no strong impacts on the electricity price, with only the later sample period showing some evidence of a long-run impact. The natural gas price shows no evidence of affecting the level of the electricity price but shows some evidence of affecting the weekly changes in the electricity price. On the other hand, and consistent with the Granger non-causality analysis, the level of the coal price is shown to have a significant positive effect on the electricity price in both periods.

In terms of the renewables production, wind power generation has a significant negative effect on the level of the electricity price. This is essentially a pure supply effect as expansion in largely exogenously determined wind power generation adds megawatts to the markets, pushing down the price. The same applies to hydropower. Additional hydro reserved pushes down the electricity price.

Miss-specification tests show no evidence of residual autocorrelation in the electricity price, implying that the specified model can capture most systematic movements in weekly electricity prices. However, normality of residuals is strongly rejected.

The bounds test for the first sub-sample rejects both null-hypothesis, allowing us to conclude that there is a significant long-run relationship between the electricity price and at least some of the independent variables. For the second sub-sample on the F-test rejects the null. The t-test fails to reject such that the bounds test is indeterminate for the shorter sample.

TABLE 3. Estimation Results of ARDL conditional model of the Nord-Pool Electricity Price

	(2008-2019)		(2013-2019)	
Parameters	Est.	S.E.	Est.	S.E.
Intercept	1.112	0.915	4.889***	1.639
Lag 1 Nord Pool Electricity Price	-0.075***	0.017	-0.112***	0.031
Lag 1 Δ Nord Pool Electricity Price	0.033	0.042	-0.172***	0.057
Lag 2 Δ Nord Pool Electricity Price	-0.175***	0.042	-0.182***	0.055
Lag 1 Brent Price	0.002	0.009	-0.018*	0.011
Δ Brent Price	0.052	0.058	-0.058	0.065
Lag 1 Δ Brent Price	-0.083	0.059	-0.047	0.067
Lag 2 Δ Brent Price	-0.017	0.058	0.062	0.065
Lag 1 U.K. Natural Gas Price	-0.024	0.026	0.000	0.028
Δ U.K. Natural Gas Price	0.424***	0.068	0.191***	0.040
Lag 1 Δ U.K. Natural Gas Price	0.181***	0.070	0.094**	0.045
Lag 2 Δ U.K. Natural Gas Price	0.12*	0.070	0.051	0.041
Lag 1 NWE Coal Price	0.115**	0.040	0.258***	0.071
Δ NWE Coal Price	0.666***	0.227	0.291	0.279
Lag 1 Δ NWE Coal Price	-0.142	0.232	-0.028	0.287
Lag 2 Δ NWE Coal Price	-0.290	0.229	-0.374	0.287
Lag 1 Nord Pool Wind Power	-	-	-0.1051***	0.026
Δ Nord Pool Wind Power	-	-	-0.1427***	0.015
Lag 1 Δ Nord Pool Wind Power	-	-	0.003	0.021
Lag 2 Δ Nord Pool Wind Power	-	-	-0.003	0.016
Lag 1 Nord Pool Hydro Reserve	-	-	-0.2961***	0.116
Δ Nord Pool Hydro Reserve	-	-	-8.496***	1.181
Lag 1 Δ Nord Pool Hydro Reserve	-	-	2.023	1.511
Lag 2 Δ Nord Pool Hydro Reserve	-	-	0.240	1.519
Lag 3 Δ Nord Pool Hydro Reserve	-	-	4.24***	1.261
R2	0.196		0.464	
# Observations	584		325	
# Parameters	16		25	
Breusch-Godfrey LM Test	10.58		7.9	
Shapiro-Wilk Normality Test	0.903***		0.944 ***	
Bounds Test				
F-test	5.22**		4.13**	
T-test	-4.456 ***		-3.62	

Note: ***,**,* denotes significance at 1%,5% and 10%. Wind and Hydro Reserve expressed in 10 000 MWh. Breusch-Godfrey LM Test is the test of the null of no serial correlation up to AR 10. The Shapiro-Wilk Normality Test is the of the null of Gaussian residuals. The F-test in the Bounds test is the test of the null that regressands in level are have no relation to the electricity price. The T-test is the test of the null that the lagged level of the electricity price is zero. Critical values for the I(0) and I(1) bounds from Pesaran, Shin, and Smith (2001).

To better illustrate the effects of a change in the independent variables on the electricity price we now report impulse response analysis. We trace out the dynamic impacts of a one standard deviation positive shock to each indenepdent variable. The y-axis of the plots refers to deviations in Mwh. from the mean electricity price, and the x-axis shows electricity price adjustments in weeks since the shocks. The shock occurs in week 10. A finite sample of impulse responses are generated by simulating from the estimated model. Dotted line refers to the mean impact, while shaded areas are 75th, 90th and 95th percentiles of the responses.

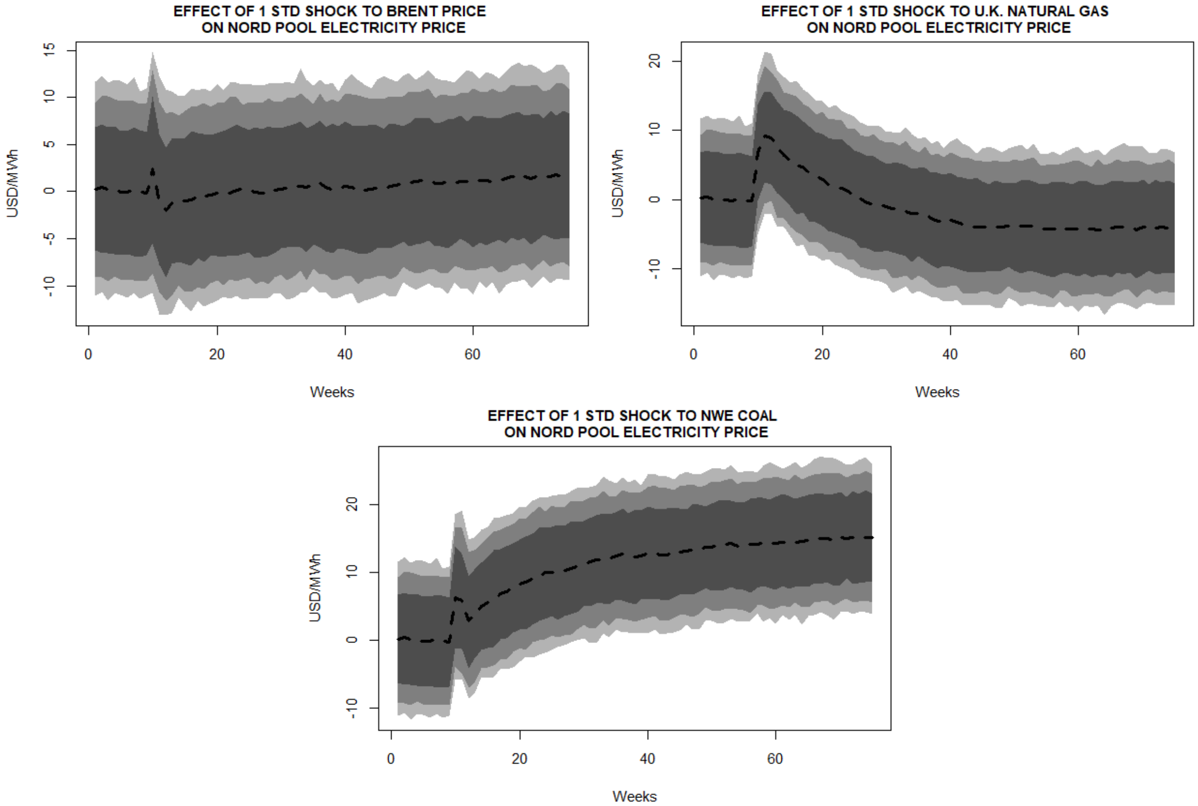

FIGURE 2. Simulated responses of electricity prices (deviation from mean) of a one standard deviation shock to the oil price, natural gas price and coal price. 2008 to 2019. Dotted line is the mean response, grey shaded areas refer to 75th, 90th and 95th percentiles.

Figure 2 shows electricity price responses to shocks to crude oil, natural gas and coal prices for the full sample model (2008 to 2019). As the plots show, there is no significant of a change in the oil price on the electricity price. A positive one standard deviation natural gas price shock leads to a short run increase in the electricity price of around 10 USD/Mwh. The effect however is only transitory as the electricity price eventually reverts to its mean. This strongly contrasts the effect of positive shock to the coal price. The impact here is to permanently raise the level of the electricity price.

Figure 3 shows the impact of shocks to hydro power reserves, wind power and the coal price for the second sample period (2013-2019). We see that there is a strong short run negative impact of a one standard deviation increase in hydro power reserves on the electricity price. However, the impact is short-lived, and prices quickly recover. This implies that variations in hydro power reserves largely impacts the short run volatility of electricity prices. The effect is quite different when we look at wind power generation. Here a one standard deviation increase in wind power generation has a strong negative permanent effect on the electricity price. We also see that the effect of the coal price remains similar as in the full sample, with a coal price increase contributing to permanently raising the electricity price.

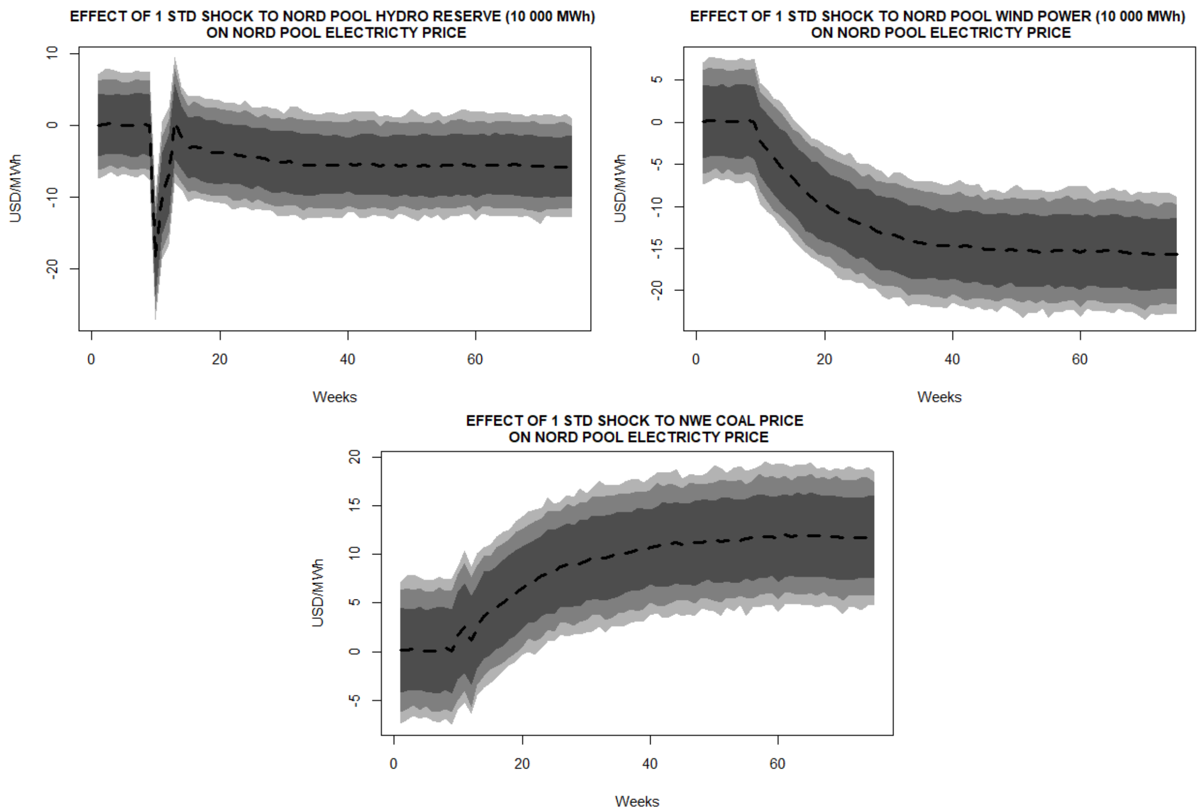

FIGURE 3. Simulated responses of Electricity prices (deviation from mean) of a one standard deviation shock to hydro reserves, wind power generation and coal price. 2013 to 2019. Dotted line is the mean response, grey shaded areas refer to 75th, 90th and 95th percentiles.

To assess the relative contribution of these variables to the electricity price we perform a simple counter-factual analysis. Using the model for the second sub-sample we fix coal prices and wind power generation at their average 2014 levels and trace out the implied electricity price in each counterfactual regime. We then contrast this with the actual price to arrive at an evaluation of the relative impact of coal and wind power generation up.

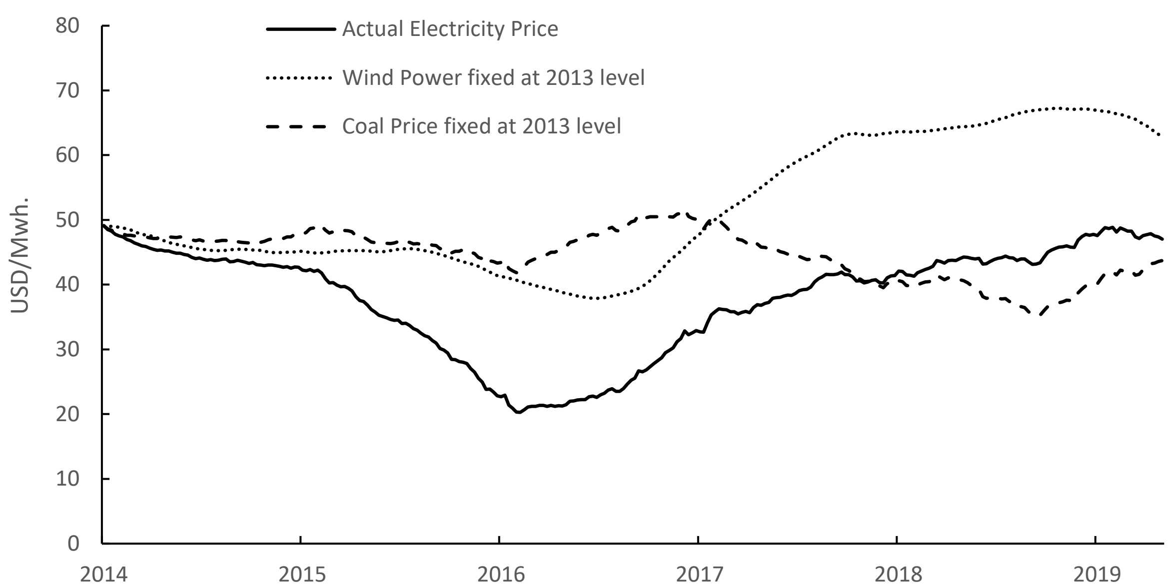

FIGURE 4. Actual and counterfactual electricity price trend with coal price and wind power generation fixed at 2013 levels. Annual average prices shown.

Figure 4 shows the results. The lines show the actual and counterfactual electricity price trends as annual averages of weekly prices. We observe that with wind power generation at 2013 levels, the actual price would be considerably higher for the entire period. This speaks to the permanent effects of adding fixed wind power capacity on the market. With fixed coal prices the electricity price would also have been higher up to 2017. This because of the declining trend in the coal price in this period keeping electricity prices down. However, towards the end of the sample the increase in the coal price has contributed somewhat to increasing the electricity price. The results here also suggest that the quantitative impacts of coal prices change, and wind power generation has been similar. In this sense both the cheaper coal and the addition of wind power generation has contributed in approximately equal amounts to the electricity price.

It should be noted that these results are only meant to highlight the quantitative significance of the coal price trend and wind power generation on the electricity price. Clearly, with 80% higher electricity price investments in other power generation, including renewables, would be higher, reducing the electricity price. In this sense, the depressing effect of the U.S. shale revolution on coal price and resulting electricity price has made renewable investments less profitable.

The Role of the U.S. Shale Gas Revolution

The results so far show that the developments of cheaper coal over the sample period has significantly contributed to keeping down the Nord-Pool electricity prices. We next explore the hypothesis that the U.S. shale gas boom has been driving the trend of cheaper coal coming to Europe. Natural gas and coal are substitutes in electricity generation. Cheap domestic U.S. natural gas has led to lower demand for coal in U.S. electricity generation. This has kept down the price of U.S. coal (Basher, 2019). Since Europe is one of the main export markets for U.S. coal, (second behind India in 2018, https://www.eia.gov/tools/faqs/faq.php?id=66&t=2), this suggests that the declining price of coal in Europe can be traced to the glut of natural gas in the domestic U.S. market.

To explore this hypothesis, we start by investigating the Granger non-causality between U.S. natural gas prices and the Nord-Pool electricity and NWE coal prices. Table 3 shows the results. Consistent with the hypothesis, we find that U.S. natural gas has been cointegrated with the European coal price and the Nord-Pool electricity price in the sample period. Furthermore, we find strong evidence that it has been the U.S. natural gas price trend that has driven the trend in the coal price and the electricity price.

TABLE 3. P-values for Granger non-causality tests, U.S. Natural Gas

H_0	*Long-Run*	*Short-Run*	*General*
U.S. Natural Gas does not Granger cause Coal	0.001	0.025	0.013
Coal does not Granger cause U.S. Natural Gas	0.723	0.582	0.746
U.S. Natural Gas does not Granger cause Electricity	0.000	0.450	0.610
Electricity does not Granger cause U.S. Natural Gas	0.666	0.428	0.570

Note: Long-Run test is based on the evidence of co-integration, where we use a 5% critical value to determine whether co-integration is present. If co-integration is detected, we test for non-adjustment to cointegration errors. Short-run is a test for Granger non-causality in a VAR in differences. General is the Toda and Yamamoto (1995) test for non-causality using a VAR in levels with additional lag added based on the maximum order of integration of the data.

The results in table 3 suggests that we can explain the effects of cheaper coal on the Nord-Pool electricity price by the U.S. natural gas price. We now test this formally be instrumenting the European coal price using the U.S. natural gas price. The instrumented coal price is the coal price as predicted by the long run weakly exogenous U.S. natural gas price. We proceed by estimating an ARDL model for coal price determination to investigate the impact of U.S. natural gas price on the coal price, and an ARDL model for the electricity price using the coal price instrumented by the U.S. natural gas price instead of the actual coal price. Results are reported in table 4, performed over the whole sample period.

TABLE 4. Conditional Model of Coal NWE price and Electricity with Instrumented Coal NWE Trend

	Coal NWE		Electricity, Coal trend instrumented by U.S. Natural Gas	
Parameters	Est.	S.E.	Est.	S.E.
Intercept	0.215	0.162	0.650	0.995
Lag 1 NWE Coal Price	-0.028***	0.008	-	-
Lag 1 Δ NWE Coal Price	0.111***	0.042	-	-

Lag 2 Δ NWE Coal Price	0.034	0.041	-	-
Lag 1 Nord Pool Electricity Price	-	-	-0.067***	0.015
Lag 1 Δ Nord Pool Electricity Price	-	-	0.026	0.041
Lag 2 Δ Nord Pool Electricity Price	-	-	-0.193***	0.041
Lag 1 Oil Price	0.004**	0.002	0.010	0.009
Δ Oil Price	0.078***	0.01	0.119**	0.057
Lag 1 Δ Oil Price	-0.003	0.011	-0.104*	0.058
Lag 2 Δ Oil Price	0.013	0.011	-0.030	0.057
Lag 1 U.K. Natural Gas	-0.009*	0.005	-0.022	0.026
Δ U.K. Natural Gas	0.038***	0.012	0.469***	0.068
Lag 1 Δ U.K. Natural Gas	0.031***	0.012	0.211***	0.070
Lag 2 Δ U.K. Natural Gas	0.015	0.012	0.148**	0.071
Lag 1 U.S. Natural Gas	0.019***	0.005	-	-
Δ U.S Natural Gas	0.063***	0.023	-	-
Lag 1 Δ U.S Natural Gas	0.013	0.023	-	-
Lag 2 Δ U.S Natural Gas	0.001	0.024	-	-
Lag 1 NWE Coal (U.S. Natural Gas)	-	-	0.084**	0.034
Δ NWE Coal (U.S. Natural Gas)	-	-	-0.204	0.190
Lag 1 Δ NWE Coal (U.S. Natural Gas)	-	-	0.017	0.186
Lag 2 Δ NWE Coal (U.S. Natural Gas)	-	-	-0.114	0.188
R^2	0.255		0.184	
# Observations	584		584	
# Parameters	16		16	
Breusch-Godfrey LM Test	5.82		14.08	
Shapiro-Wilk Normality Test	0.919***		0.908***	
Bounds Test				
F-test	5.013**		5.188**	
t-test	-3.468*		-4.320*	

Note: ***,**,* denotes significance at 1%,5% and 10%. Wind and Hydro Reserve expressed in 10 000 MWh. Breusch-Godfrey LM Test is the test of the null of no serial correlation up to AR 10. The Shapiro-Wilk Normality Test is the of the null of Gaussian residuals. The F-test in the Bounds test is the test of the null that regressands in level are have no relation to the electricity price. The T-test is the test of the null that the lagged level of the electricity price is zero. Critical values for the I(0) and I(1) bounds from Pesaran, Shin, and Smith (2001).

The first columns show the results for the conditional model of coal prices. The results confirm the significant impact of the U.S. natural gas price on the NEW coal price. Note that the result controls for the impact of crude oil and U.K. natural gas price on the coal price. The bounds test rejects the null of no level relationship in the prices. We next use the estimated level relationship between the U.S. natural gas price and coal price to generate the instrumented coal price. The second column shows the relationship between the instrumented coal price and the electricity price. The results confirm that the coal price, as explained by the U.S. natural gas price, has a significant positive relationship to the level of the Nord-Pool electricity price.

Conclusion

We have provided evidence that 1) lower European coal prices has contributed to reducing the Nord-Pool electricity equivalent in magnitude to the introduction of wind power capacity to power generation, and 2) that the trend in the European coal price can be explained by the unique U.S. natural gas price trend generated by the shale gas boom in the U.S. Indeed, previous research has shown that the shale gas boom has decoupled U.S. natural gas prices from the crude oil price, creating a separate unique natural gas price trend in the U.S. (Erdős, 2012, Oglend et al, 2015). Our results suggest that the U.S. shale boom has affected European energy markets through access to cheaper coal, which has not faced the same export restriction in the U.S. as crude oil and natural gas.

Since coal prices influences the electricity price, what happens to coal is relevant to the economics of renewables investments in Europe. Our results show that this will depend on the U.S. energy market if coal is produced and exported. This means that U.S. energy market policies with regards to unconventional oil and natural gas will be of importance to electricity in Europe. For instance, if U.S. exports of natural gas raises the U.S. natural gas price, this will reduce the relative price of coal in the U.S. which will stimulate to more coal power generation. However, if coal prices increase again this will raise the European electricity price, improving the economics of further renewables expansion in Europe. This highlights the importance of the global nature of energy markets connections, even when single product markets such as natural gas are regional.

References

Basher, S.A., 2019. “Oil prices and other energy commodities.” *Routledge Handbook of Energy Economics*, pp .376.

Elliott, G., Rothenberg, T.J. and Stock, J.H., 1992. Efficient tests for an autoregressive unit root. *NBER* working paper.

Erdős, P., 2012. “Have oil and gas prices got separated?” *Energy Policy*, *49*, pp.707-718.

Frydenberg, Stein, Joseph I. Onochie, Sjur Westgaard, Nora Midtsund, and Hanna Ueland. 2014. "Long-term relationships between electricity and oil, gas and coal future prices—evidence from Nordic countries, Continental Europe and the United Kingdom." *OPEC Energy Review* 38, no. 2: 216-242.

Hirth, Lion. 2018. "What Caused the Drop in European Electricity Prices? A Factor Decomposition Analysis." *The Energy Journal* 39, no. 1.

Johansen, S., 1988. “Statistical analysis of cointegration vectors.” *Journal of economic dynamics and control*, *12*(2-3), pp.231-254.

Kwiatkowski, D., Phillips, P.C., Schmidt, P. and Shin, Y., 1992. “Testing the null hypothesis of stationarity against the alternative of a unit root.” *Journal of econometrics*, *54*(1-3), pp.159-178.

Mohammadi, Hassan. 2009. "Electricity prices and fuel costs: Long-run relations and short-run dynamics." *Energy Economics* 31, no. 3: 503-509.

Oglend, Atle, Morten E. Lindbäck, and Petter Osmundsen. 2015. "Shale gas boom affecting the relationship between LPG and oil prices." *The Energy Journal*, 265-286.

Oglend, Atle, Tore Selland Kleppe, and Petter Osmundsen. 2016. "Trade with endogenous transportation costs: The case of liquefied natural gas." *Energy Economics* 59 (2016): 138-148.

Oglend A, Osmundsen P, Kleppe TS. 2020. «Time Commitments in LNG Shipping and Natural Gas Price Convergence.” *Energy Journal*. 41(2).

Pesaran, M.H., Shin, Y. and Smith, R.J., 2001. “Bounds testing approaches to the analysis of level relationships.” *Journal of applied econometrics*, *16*(3), pp.289-326.

Toda, H.Y. and Yamamoto, T., 1995. “Statistical inference in vector autoregressions with possibly integrated processes.” *Journal of econometrics*, *66*(1-2), pp.225-250.