Buffering the Energy Crisis:
Renewables Moderate the Pass-Through of Gas Prices in Electricity Markets

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EEA-ESEM Rotterdam
Contributed Session: Energy Market Transition
August 26nd, 2024

Established fact 1: Power prices follow gas prices

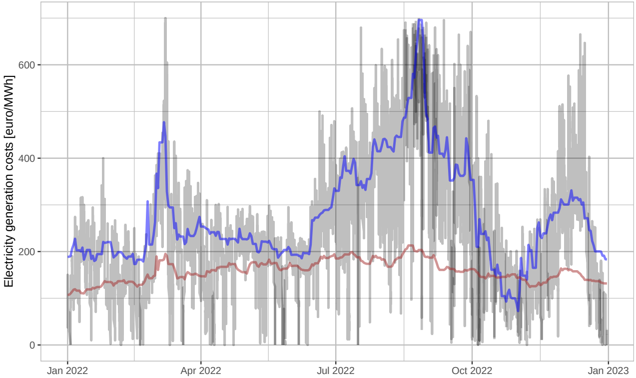

Figure 1: Germany 2022: Power prices have high intra-day volatility, but follow elevated gas prices more than coal prices (Merit Model).

- Gas as price driver in ($\approx$ 55%) of the time, while its share in power generation is only 11% (Gasparella et al., 2023, ENTSO-E, 2023b)

Established fact 2: Renewables lower power prices

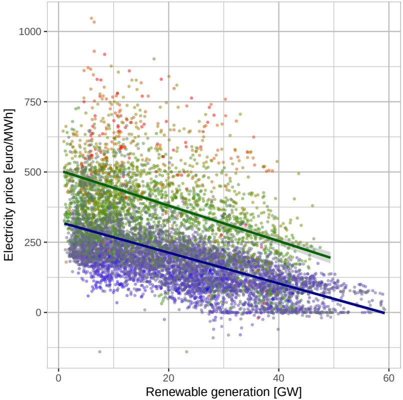

Figure 2: Hourly 2022 electricity price at low, elevated and peak coal + gas prices. Green line for August.

- Merit-order effect well studied in the literature (see e.g. Sensfuß et al., 2008, Sáenz de Miera et al., 2008, Gelabert et al., 2011, Würzburg et al., 2013, Clò et al., 2015)
- Power price $P_t = f(R_t)$, $\frac{\partial f}{\partial R} < 0$

Established fact 3: Renewables lower fossil fuel generation

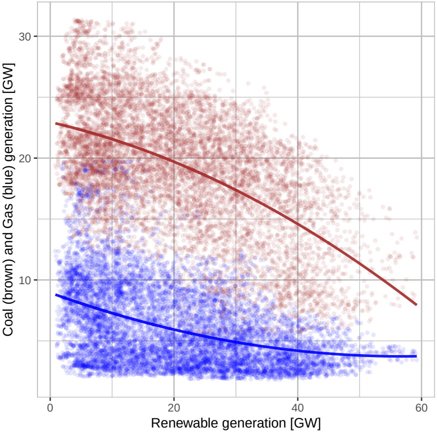

Figure 3: Hourly coal and gas generation in 2022 (dots) and correlation with renewable supply (lines).

- Low (marginal) cost renewables crowd out expensive fossil fuels (see e.g. Abrell et al., 2019, Liski and Vehviläinen, 2020, Ballester and Furió, 2015)
- Merit-order: Replacement of gas (convex) takes place before coal replacement (concave)
- Residual demand for fossil fuels: $F_t = g(D_t, R_t)$, $\frac{\partial g}{\partial R} < 0$, with load D_t and renewables R_t

Research question

Existing literature

- Gas price pass-through: $\frac{\partial f}{\partial P_{gas}} > 0$ ($\simeq 1$ in peak-hours, see Fabra and Reguant, 2014, Hintermann, 2016, Linn and Muehlenbachs, 2018)
- Merit-order effect: $\frac{\partial f}{\partial R} < 0$, ($\simeq -0.10$ €/MWh per TWh in Würzburg et al., 2013 to $\simeq -0.25$ in Clò et al., 2015.
- Substitution effect: $\frac{\partial g}{\partial R} < 0$, ($\simeq -0.3$ in Abrell et al., 2019 to $\simeq -0.6$ in Liski and Vehviläinen, 2020)

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Research Question

- by connecting all three literature strands: do renewables reduce power prices by limiting the pass-through of gas prices?
  - can we catch the merit-order price mechanics using second/third order derivatives?
  - Hypothesis: $\frac{\partial^2 f}{\partial P_{gas} \partial R} < 0$; $\frac{\partial^3 f}{\partial P_{coal} \partial R^2} < 0$

Contribution and Policy relevance

Contribution

- Identifying the merit-order effect as a shift from gas to coal to renewables as price drivers (conditional power price dependence)
- To the best of our knowledge: first empirical study of gas price pass-through in electricity markets during the 2022 energy crisis

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Time Frame

- higher order derivatives/interaction effects need considerable variation
- 2022 energy crisis provides volatility in gas, coal, and power prices
- intermittent renewables have substantial share in Germany ($> 33\%$)

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Policy relevance

- Quantifying renewables double dividend: reducing CO2 emissions and leverage of autocratic states (that supply gas) over Europe

Identification

1. At any point in time, increased renewables push out the marginal unit
2. Where we are in the supply order depends on (1) the renewable supply and (2) overall demand

Power price: $P_t = f(P_{gas,t}, P_{coal,t}, F_t = g(D_t, R_t))$

- F_t: fossil fuel power residual demand
  - endogenous to prices

$\Rightarrow$ instrument F_t by sunshine/wind speed $\times$ time of the day

- Second stage: $P_t = f(P_{f,t}, \widehat{F}_t, \widehat{F}_t^2)$
- First stage: $P_{f,t}^m F_t^n = g(W_t, S_t; t)$ (for $m \in \{0, 1\}, n \in \{1, 2\}$)

calibration

Empirical Strategy: Hourly Conditional Effects Model

$$P_t = \sum_f \left(\beta_{0,f} P_{f,t} + \beta_{1,f} F_t P_{f,t} + \beta_{2,f} F_t^2 P_{f,t} \right) + \gamma_0 + \gamma_1 F_t + \gamma_2 F_t^2 + \mathcal{F}(t) + \varepsilon_t \quad (1)$$

- P_t: spot market electricity prices
- $P_{f,t}$: calibrated electricity production costs for fuel f $\in \{gas, coal\}$
- F_t: fossil fuel residual demand (mean zero, range one)
- $\mathcal{F}(t)$: Fourier series that mimic time fixed effects

transform.

Preliminary Results: Conditional Fuel Price Pass-Through

Table 1: Merit model fuel price loading

Dependent: Electricity Price (EUR/MWh)	IV
$P_{c,t}$ (price coal $+CO_2$)	0.90***
$P_{c,t} \cdot F_t$	−1.50**
$P_{c,t} \cdot F_t^2$	−5.74***
$P_{g,t}$ (price gas + CO_2)	0.72***
$P_{g,t} \cdot F_t$	2.11***
$P_{g,t} \cdot F_t^2$	0.32
F_t (Coal+Gas)	70
F_t^2 (Coal+Gas^2)	724***
constant	−123**
$\mathcal{F}(2d + 2w)$	Y
N	8448
R^2_{adj}	0.85

Dependent variable mean=238, sd=147, independent variables F_t, F_t^2 are normalized to mean zero. All models use only dates with gas production costs above coal. Newey and West (1987) standard errors. Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05.

- Both coal and gas have substantial base pass-through (0.90/0.72)
- Gas pass-through increases with fossil fuel demand (2.11)
- Coal price pass-through is strongly concave (-5.74)

Preliminary Results: Graphical Representation

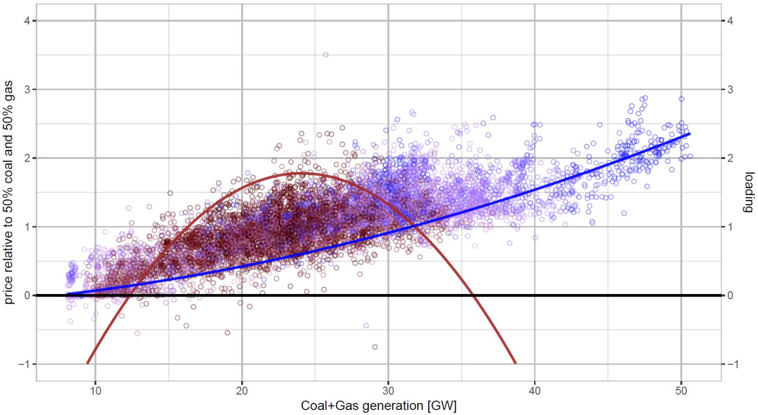

Figure 4: Right scale: conditional price loadings of coal (brown line) and gas (blue line). Left scale: elec prices relative to average fuel costs (dots), brown = high ratio coal/gas; blue = low ratio coal/gas in generation

Preliminary Results: First stage

Table 2: Merit model: fossil fuel substitution in quantities

Dependent: Residual Fossil Fuel Demand F_t	IV
S_t	-0.526^{***}
W_t	-0.570^{**}
constant	-0.001^{**}
$\mathcal{F}(2d + 2w)$	Y
N	8448
R^2_{adj}	0.79

Variables normalized to mean zero. All models use only dates with gas production costs above coal. Newey and West (1987) standard errors. Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05.

- Both wind and solar replace more than half of fossil fuel generation
- crowding out at higher levels than in Abrell et al., 2019 and comparable to Liski and Vehviläinen, 2020
- Moderating effect of renewables on gas price pass-through
  - Solar: 0.526 * average solar * 2.11 = 0.184 (25.5%)
  - Wind: 0.570 * average wind * 2.11 = 0.348 (48.4%)

Counterfactual Analysis: Model

$$R_t = \mathcal{P}(S_t, W_t; 2)\mathcal{F}(t)\mathcal{P}(P_{f,t}; 1) + \mu_t \quad (2)$$

$$X_t = \mathcal{P}(\widehat{R}_t; 2)\mathcal{F}(t)\mathcal{P}(P_{f,t}; 1) + \mu_t \quad (3)$$

- ($\hat{R}_t$) R_t: (Predicted) renewable energy (Sun + Wind) generation
- X_t: second stage dependent variable (e.g. prices, generation from coal, gas, hydro etc.)

- Manipulating $\hat{R}_t$ allows for counterfactual effects of changes in renewables on prices and other energy sources

Counterfactual Analysis: +1 TWh of Solar and Wind

Table 3: Scenario analysis: basic outcomes

	quantities			prices		
	Reprod	+Sun	+Wind	Reprod	+Sun	+Wind
S (solar power generation)	55.4	+1.0	0	228	-2.66	-0.53
W (wind power generation)	125.3	0	+1.0	181	-0.53	-1.00
C (coal power generation)	166.4	−0.26	−0.34	259	-0.72	-0.63
G (gas power generation)	53.5	−0.17	−0.15	272	-0.64	-0.59
H (net hydro pumped generation)	-3.8	−0.16	−0.08	-116	-3.66	-1.29
R (residual power generation)	97.4	−0.02	−0.01	240	-0.77	-0.68
T (net trade)	−27.3	−0.40	−0.39	52	-1.47	-1.67
Q (total demand)	482.7	+0.06	+0.06	239	-0.83	-0.69

Columns 1 and 4 present reproductions of observed data. Column 2,3,5,6 present changes. First 3 columns in TWh. Last 3 columns in €/MWh. Prices are weighted with quantities of column 1. Unweighted average price of 238 €/MWh, decreasing by **0.78 and 0.66 €/MWh** for +Sun and +Wind counterfactual scenarios, respectively. Residual power generation includes nuclear, biomass, waste, oil, hydro run of river, hydro reservoir, geothermal, other non-specified.

Counterfactual Analysis: Rent shifts

	$P\Delta Q$		$\mathbf{\Delta P}Q$		$\Delta(PQ)$	
	+Sun	+Wind	+Sun	+Wind	+Sun	+Wind
Solar	+227	0	−147	−30	80	−30
Wind	0	+181	−67	−126	−67	55
Coal	−51	−52	−120	−103	−171	−153
Gas	−43	−29	−33	−32	−76	−61
Hydro	−33	−14	15	4	−18	−10
Residual	−4	−2	−75	−67	−79	−69
Trade	−93	−75	24	28	−69	−47
Demand	+17	+15	+401	+333	418	348

First two 4 columns present changes in million €. Column 5 represents the sum of 1 and 3, column 6 the sum of 2 and 4.

- 1TWh additional wind reduces **price** paid to coal+gas, reducing rents by 135 euro/MWh. Consumer benefit from reduced fuel exposure.

Conclusion

Key Findings

- Large merit-order effect during the 2022 Energy Crisis
  - Estimated per TWh MOE: -0.78 €/MWh
  - Mechanism: Renewables substitute first for gas and then for coal (at a rate of about 50%)

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  - Estimated per TWh MOE: -0.78 €/MWh
  - Mechanism: Renewables substitute first for gas and then for coal (at a rate of about 50%)
- Renewables mitigated the pass-through of soaring gas prices
  - Compared to zero renewables, average solar (wind) reduced gas price loadings by 25.5% (48.4%)

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Key Findings

- Large merit-order effect during the 2022 Energy Crisis
  - Estimated per TWh MOE: -0.78 €/MWh
  - Mechanism: Renewables substitute first for gas and then for coal (at a rate of about 50%)
- Renewables mitigated the pass-through of soaring gas prices
  - Compared to zero renewables, average solar (wind) reduced gas price loadings by 25.5% (48.4%)
- Rents flow from fossil fuels to consumers at rates above 135 €/MWh
  - Also due to slow adaptation of fossil power plants in the short-term
  - Despite cannibalization, solar and wind energy benefit net from their expansion

Thank you very much!

Data: Variables and Sources

Data for Germany 2022

- Weather data[1]
  - Hourly sunshine (J/cm2) and Wind speed (m/s)
  - Measurements from 17 weather stations
  - Selection based on the regional distribution of renewables
- Hourly day-ahead electricity prices[2] (€/MWh)
- Daily day-ahead coal, gas (€/MWh), ETS (€/tCO2) prices[3]
- Hourly day-ahead load, wind, solar generation[4] (MWh)

summary statistics stations

1 Deutscher Wetterdienst (2022a), (2022b), 2 Ember (2023), 3 Refinitiv (2023), 4 ENTSO-E (2023a)

Data: Summary Statistics

Table 4: Summary Statistics: Selected Variables

Variable	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	Freq.	N
Elec Price (€/MWh)	-134	135	210	238	312	1047	H	8759
Gas Costs (€/MWh)	73	200	238	278	343	696	D	8759
Coal Costs (€/MWh)	108	143	160	159	175	213	D	8759
Solar (MWh)	0	0	252	6325	10444	37784	H	8759
WindGen (MWh)	284	5270	10489	14154	21260	46600	H	8759
RenewGen (MWh)	1004	9250	18922	20479	29739	64950	H	8759

Units, distribution, frequency, and number of observations of all main raw variables. Only coal, gas, and ETS prices are measured daily for all working days in 2022. data

Data: Weather Measurement Stations

Figure 5: Weather stations in yellow for radiation and blue for wind

Transformation of Fossil Fuel Generation

Linear Term:

- transform $\text{Coal}_t + \text{Gas}_t = \text{Fuels}_t$ into F_t

$$F_t = \frac{\text{Fuels}_t - \frac{1}{T}\sum_t \text{Fuels}_t}{\max\{\text{Fuels}_1, \ldots, \text{Fuels}_T\} - \min\{\text{Fuels}_1, \ldots, \text{Fuels}_T\}} \tag{4}$$

Quadratic Term:

- transform F_t into F_t^2

$$F_t^2 = 4 \cdot (F_t^2 - \frac{1}{T}\sum_t F_t^2) \tag{5}$$

empirical model

Calibration: Coal and Gas Marginal Costs

Gas Prices

$$\psi_{gas,t} = (\text{Gas}_t + 0.2 \cdot \text{ETS}_t)/0.5 \tag{6}$$

Coal Prices

$$\psi_{coal,t} = (\text{Coal}_t/8.1 + 0.38 \cdot \text{ETS}_t)/0.4 \tag{7}$$

Identification

First Stage Results

Table 5: First stage models

	(1)	(2)	(3)	(4)	(5)
	F_t	F_t^2	F_t	F_t^2	F_t
	OLS	OLS	OLS	OLS	IV
$\mathcal{P}(S_t, W_t; 1)$	Y				
$\mathcal{P}(S_t, W_t; 2)$		Y			
R_t					-0.61***
R_t^2					0.04***
$\mathcal{F}(2d \cdot 2w \cdot 2y) + P(1y)$	Y	Y			Y
$\mathcal{P}(S_t, W_t; 2) \cdot (\mathcal{F}(d2 \cdot w2 \cdot y2) + \mathcal{P}(1y))$			Y	Y	
N	8447	8447	8447	8477	8477
R^2_{adj}	0.65	0.36	0.75	0.67	0.79

The last column presents $F_t = \mathcal{P}(R_t; 2) + \mathcal{F}(t) + \mathcal{P}(P_{f,t}; 1) + \mu_t$. Note that the fourth column s substantially improves on column two by interacting the time Fourier series with the instrument sun and wind. instrumentation

Preliminary Results

Table 6: Merit model fuel price loading, polynomial transformation

	dependent: electricity price			
	(1) OLS	(2) OLS	(3) IV	(4) IV
$P_{c,t}$ (price coal $+CO_2$)	0.95***	0.90***	0.97***	0.90***
$P_{c,t} \cdot F_t$	-1.18*	-1.42**	-0.95*	-1.50**
$P_{c,t} \cdot F_t^2$	-5.47***	-5.36***	-5.84***	-5.74***
$P_{g,t}$ (price gas $+ CO_2$)	0.71***	0.72***	0.69***	0.72***
$P_{g,t} \cdot F_t$	2.05***	2.05***	2.08***	2.11***
$P_{g,t} \cdot F_t^2$	0.33*	0.34*	0.31	0.32
F_t (Coal+Gas)	60	70	37	70
F_t^2 (Coal+Gas^2)	681***	665***	740***	724***
constant	-123***	-119***	-119***	-123***
$\mathcal{F}(2d+2w)$		Y		Y
N	8448	8448	8448	8448
R^2_{adj}	0.82	0.85	0.82	0.85

Dependent variable mean=238, sd=147, independent variables F_t, F_t^2 are normalized to mean zero.Model 3 and 4 use electricity generation by renewables (R_t, R_t^2) interacted with $\mathcal{F}(2d \cdot 2w \cdot 2y)$ as instrument for F_t and F_t^2 (and similarly the interactions with $P_{c,t}$ and $P_{g,t}$). All models use only dates with gas production costs above coal. Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 ' ' 1. Newey and West (1987) standard errors.

Robustness: Renewables instead of Fossil Fuel Demand

Table 7: Merit model fuel price loading interacting with renewable generation

	dependent: electricity price	
	(1)	(2)
	IV	IV
$P_{c,t}$ (price coal $+CO_2$)	0.72*	0.93***
$P_{c,t} \cdot R_t$		0.55
$P_{c,t} \cdot R_t^2$		-0.80***
$P_{g,t}$ (price gas $+ CO_2$)	0.82***	0.66***
$P_{g,t} \cdot R_t$		-0.53***
$P_{g,t} \cdot R_t^2$		-0.13*
R_t (Sun+Wind)	-257***	-206***
R_t^2 (Sun+Wind)^2	2	147***
$\mathcal{F}(2d+2w+2y)+\mathcal{P}(1y)$	Y	Y
N	8423	8423
R^2_{adj}	0.83	0.84

Dependent variable mean=238, sd=147, independent variables R_t, R_t^2 are normalized to mean zero. All models use only dates with gas production costs above coal. Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 ' ' 1. Newey and West (1987) standard errors.

References I

Abrell, J., Kosch, M., & Rausch, S. (2019).Carbon abatement with renewables: Evaluating wind and solar subsidies in germany and spain. *Journal of Public Economics*, *169*, 172–202.

Ballester, C., & Furió, D. (2015).Effects of renewables on the stylized facts of electricity prices. *Renewable and Sustainable Energy Reviews*, *52*, 1596–1609. https://doi.org/10.1016/j.rser.2015.07.168

Clò, S., Cataldi, A., & Zoppoli, P. (2015).The merit-order effect in the italian power market: The impact of solar and wind generation on national wholesale electricity prices. *Energy Policy*, *77*, 79–88. https://doi.org/10.1016/j.enpol.2014.11.038

Deutscher Wetterdienst. (2022a). Climate data center (cdc) - observations germany climate hourly solar [Accessed: May 7, 2023]. https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/hourly/solar/

Deutscher Wetterdienst. (2022b). Climate data center (cdc) - observations germany climate hourly wind [Accessed: May 7, 2023]. https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/hourly/wind/historical/

Ember. (2023, March). European wholesale electricity price data [Accessed: March 18, 2023]. https://ember-climate.org/data-catalogue/european-wholesale-electricity-price-data/

ENTSO-E. (2023a). Actual generation per production type [16.1.b&c] [Accessed: March 5, 2023]. https://transparency.entsoe.eu/generation/r2/actualGenerationPerProductionType/show

ENTSO-E. (2023b). Total load - day ahead - actual [Accessed: May 17, 2023]. https://transparency.entsoe.eu/load-domain/r2/totalLoadR2/show

References II

Fabra, N., & Reguant, M. (2014).Pass-through of emissions costs in electricity markets. *The American Economic Review*, *104*(9), 2872–2899. Retrieved June 3, 2024, from http://www.jstor.org/stable/43495336

Gasparella, A., Koolen, D., & Zucker, A. (2023). *The merit order and price-setting dynamics in european electricity markets* (tech. rep. No. JRC134300). European Commission. Petten.

Gelabert, L., Labandeira, X., & Linares, P. (2011).An ex-post analysis of the effect of renewables and cogeneration on spanish electricity prices. *Energy Economics*, *33*, S59–S65. https://doi.org/10.1016/j.eneco.2011.07.027

Hintermann, B. (2016).Pass-through of co2 emission costs to hourly electricity prices in germany. *Journal of the Association of Environmental and Resource Economists*, *3*(4), 857–891.

Linn, J., & Muehlenbachs, L. (2018).The heterogeneous impacts of low natural gas prices on consumers and the environment. *Journal of Environmental Economics and Management*, *89*, 1–28. https://doi.org/10.1016/j.jeem.2018.02.002

Liski, M., & Vehviläinen, I. (2020).Gone with the wind? an empirical analysis of the equilibrium impact of renewable energy. *Journal of the Association of Environmental and Resource Economists*, *7*(5), 873–900.

Refinitiv. (2023, February). Ice-coal rotterdam (lmccs00), rfv natural gas ttf nl (trnlttd), eex-eu co2 (eexeuas), us$ to euro (useursp) [Accessed: February 17, 2023]. https://www.refinitiv.com/en/products/datastream-macroeconomic-analysis

Sáenz de Miera, G., del Río González, P., & Vizcaíno, I. (2008).Analysing the impact of renewable electricity support schemes on power prices: The case of wind electricity in spain. *Energy Policy*, *36*(9), 3345–3359. https://doi.org/10.1016/j.enpol.2008.04.022

References III

Sensfuß, F., Ragwitz, M., & Genoese, M. (2008). The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in germany. *Energy Policy*, *36*(8), 3086–3094. https://doi.org/10.1016/j.enpol.2008.03.035

Würzburg, K., Labandeira, X., & Linares, P. (2013). Renewable generation and electricity prices: Taking stock and new evidence for germany and austria. *Energy Economics*, *40*, S159–S171. https://doi.org/10.1016/j.eneco.2013.09.011