Assessing the impact of wind and solar energy on power prices

In this study we assess the hypothesis that higher shares of wind and solar energy in the power mix result in lower power prices and higher weather induced power price volatility

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Introduction

The variable costs associated with solar and wind energy are very small in comparison to traditional energy sources that typically burn fuel to generate (thermal) power. Therefore, the production of solar and wind energy is associated with lower power prices in the short-term. We assessed the statistical significance of this effect using weekly and monthly data from five different European countries. We find strong statistical evidence for negative contributions of renewables to monthly and weekly changes in power prices. Changes in wind energy show the strongest marginal effect, which is consistent with the overall larger share of wind energy in power generation and the higher load factor of wind turbines compared to solar panels; one MW capacity of wind energy generates much more power than one MWp of solar capacity.

Modelling power prices

To assess the marginal effects of changes in the supply of wind and solar energy on power prices we estimate the model shown in equation 1.

Equation 1: Power price model

$$\Delta Power\ price_{it} = \propto_i$$
$$+\beta_1 \Delta Solar\ share_{it}$$
$$+\beta_2 \Delta Wind\ share_{it}$$
$$+\beta_3 (\Delta Solar\ share_{it} * \Delta Wind\ share_{it})$$
$$+ \beta_4 (\Delta Solar\ share_{it} * \Delta Nuclear\ share_{it})$$
$$+\beta_5 (\Delta Wind\ share_{it} * \Delta Nuclear\ share_{it})$$
$$+\beta_6 (\Delta Solar\ share_{it} * \Delta Wind\ share_{it} * \Delta Nuclear\ share_{it})$$
$$+\beta_7 \Delta Total\ power\ production_{it}$$
$$+\beta_8 \Delta CO2\ price_t$$
$$+\beta_9 \Delta Gas\ price_t$$
$$+\beta_{10} \Delta Coal\ price_t$$
$$+\beta_{11} (\Delta CO2\ price_t * \Delta GAS\ price_t)$$
$$+\beta_{12} (\Delta CO2\ price_t * \Delta Coal\ price_t)$$
$$+\beta_{13} (\Delta Gas\ price_t * \Delta Coal\ price_t)$$
$$+\beta_{14} (\Delta CO2\ price_t * \Delta Gas\ price_t * \Delta Coal\ price_t)$$
$$+\epsilon_{it}$$

To deal with potential unit roots due to seasonality and economic growth we regress the first differences computed as percentage growth percentages (denoted by Δ). $\propto_i$ denotes the intercept coefficient for country i, and ϵ_{it} captures the error term for country i at time t.

To capture the effects of an increase in intermittent sources in the power mix we include the shares of wind and solar power in the regressions as well as the product of both to capture any additional effects if both shares have increased.

Logically, if power demand is low, less power is produced, and the shares of solar and wind energy will be higher since those will not necessarily decrease proportionately with the total power production. To control for lower prices caused by lower demand rather than more abundant solar and wind power, we included the first differences in total power production.

To control for the share of nuclear energy, which also has variable costs per MWh close to zero, we added interaction effects with wind and solar power.

Commodity and carbon prices are important drivers of power prices too. To control for any non-linearities and substitution effects between different fossil energy sources we include the cross terms of the commodity prices and the CO2 price.

Finally, all panel regressions include a fixed effects term to control for non-dynamic country characteristics.

The dataset

We obtained realisations of day ahead base load power prices from the Thomson Reuters Refinitiv Eikon platform for Germany, France, Spain, Netherlands, Belgium, Great Britain and six Italian regional power markets. We also obtained the power generation by energy source for every country or region. For the Netherlands and Great Britain, we did not have generation data for solar energy, so we synthetically created a series on the basis of weather data. This is explained in the box. Gas Coal and CO2 prices are obtained from the Thomson Reuters Refinitiv Eikon platform. For Gas prices, we compute the average over the major European Gas Types. For Coal, we take the average over the major global Coal price indices. See the Table in the annex for more information.

Synthetic solar series for the Netherlands and the UK.

To find a substitute for generation data of solar panels for the Netherlands and the UK we estimated this figure with meteorological data and information on the annual capacity growth in solar energy.

For the Netherlands, we used daily hours of sunshine as measured by the meteorological station of the Bilt (Central Netherlands). As a measure for the strength of solar radiation and the amount of energy generated with zero sun hours, we used the difference between sunrise and sunset as a proxy of the time of the year. For the daily increase in capacity growth we interpolated the annual growth to daily growth rate, assuming that capacity growth for solar energy is evenly distributed over the year. We used this to compile a capacity scaling factor which equalled 1 at the 31 of December 2017 and 3.5 in March 2021.
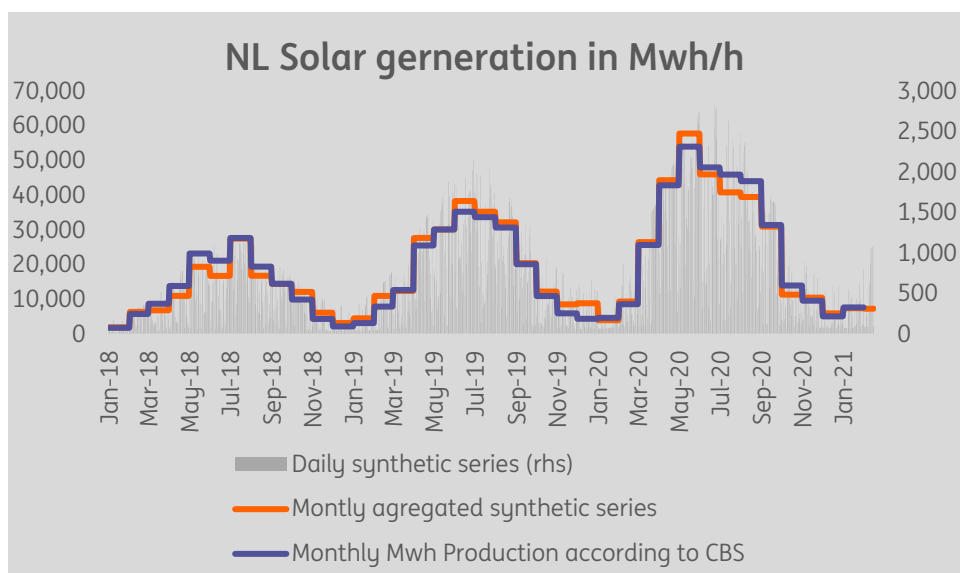
The formula used to estimate the daily generated solar power is:

$$Solar\ power_t = \theta C_t\big(\alpha + \beta_1 Lenght\ of\ day_t + \beta_2(Length\ of\ day_t\ *\ Sun\ hours_t)\big) + \varepsilon_t$$

Where:

β_1 equals the amount of energy a solar panel produces if the number of sunshine hours is zero. This is dependent on the length of day for two reasons. First, the length of day equals the amount of basic light exposure on a given day. Second, an hour of light exposure during summer months will generate more energy than during the winter. The day length is also an appropriate proxy for the relative strength of the sun, since this depends on the sun angle which again is a determinant of the relative day length. β_2 is the amount of energy a solar panel produces during an hour of sunlight, given the solar strength at that time of the year, for which we control by multiplying by the length of the day. α is a constant to capture any bias that is not captured by β_1 and should be equal to zero. To scale the index to a macro level, we first multiply the energy generated by a solar panel by the capacity growth scaling factor C_t and then multiply everything with a general scaling factor θ to align the index with number MWh/h actually generated. Subscript t denotes the time, and ε_t denotes an error term assumed to be normally distributed with a zero mean.

To estimate θ, α, β_1, and β_2,, we used monthly solar power data by the Netherlands Statistics (CBS). We computed the squared differences for the monthly sums of daily estimated solar power with the data provided by the CBS. Then we minimised the sum of squared differences by altering the coefficients using a gradient decent method with a multi-start approach to work around any possible local minima for the sum of squares. The daily estimation results, the monthly aggregated series as well as the actual monthly series by the CBS are shows in the following chart:

NL Solar gerneration in Mwh/h

Daily synthetic series (rhs)

Montly agregated synthetic series

Monthly Mwh Production according to CBS

For the UK we used a similar approach to fill in the missing data for solar power generation. However, since we only had access to monthly average data for the hours of sunshine in Great Britain, we could not estimate a higher than monthly frequency. For the UK, we aligned the series with the quarterly totals of generated solar power sourced from the UK National Statistics office. The monthly frequency of the solar data means however that we can only include the UK in the monthly regressions.

For the weekly data we computed seven-day averages of the levels. We only included the averages for the last day of each week in the data set such that we did not have any overlap in the rolling windows averages. Then, we computed the first differences for each variable such that each observation denotes the percentual week on week increase in the weekly average of the variable. We used the same approach to compute the monthly dataset in which we used 28-day averages and only included the last day of each month, also to exclude any overlap in the averages.

A series of Housman tests yielded sufficient statistical evidence to assume stationarity for the weekly data. For the monthly data we found one exception for a control variable ($\Delta Coal\ price$). However, since the evidence for stationarity was only mildly insignificant ($P>0.12$), the Coal price is not really a variable of interest, and the unit root seems not to be present in the dependent variable, we decided to let it be.

To deal with heteroscedasticity and non-normal distribution of the variables we estimate all regressions with heteroskedasticity and auto correlation consistent (HAC) standard errors.

Global variables

Variable	Specifics	Data source
Average gas price	Computed as the average over major European Day ahead indices (CEG, CZV, ETF, GPL, NCG, NRD, TTF, ZTP)	Thomson Reuters Refinitiv
CO2 price	1st Future position	EEX via Thomson Reuters Refinitiv
Average coal price	Computed as the average over Australian, Chinese Colombian, Baltic and South African coal.	Thomson Reuters Refinitiv

Country specific variables

Country and specifics	Price data source	Production data source
Germany: Included	EPEX Base - Day ahead prices Thomson Reuters Refinitiv.	Data from EEX sourced via Thomson Reuters Refinitiv
France: Included	Base - Day ahead prices Thomson Reuters Refinitiv.	Data from RTE Eco2Mix sourced via Thomson Reuters Refinitiv
Spain: Included	Base - Day ahead prices Thomson Reuters Refinitiv.	Data from Red Electrica de Espana, sourced via Thomson Reuters Refinitiv
Netherlands: included	Base - Day ahead prices Thomson Reuters Refinitiv.	EEX and ENTSO-E data, sourced via Thomson Reuters Refinitiv. Solar data estimated on the basis of KNMI weather station data, Solar energy capacity growth data by the CBS and monthly solar production data by the CBS
Belgium: Included	Base - Day ahead prices Thomson Reuters Refinitiv.	Data sourced from Elia via Thomson Reuters Refinitiv.
Great Britain: included in monthly, not weekly regressions	N2EX Base - Day ahead prices Thomson Reuters Refinitiv.	Data sourced from Elexon via Thomson Reuters Refinitiv, Solar data estimated on the basis of meteo data and quarterly production data by the UK national statistics office
Italy: included as 6 different regions (north, central north, central south, south, Sicily and Sardinia)	Base - Day ahead prices Thomson Reuters Refinitiv.	Terna and ENTSO-E data, sourced via Thomson Reuters Refinitiv
Ireland: not included	No price data available	No solar generation data available
Scandinavian countries: not included	Multiple power price regions via Thomson Reuters Refinitiv	No power generation data available on the same aggregation level as the price data (generation at country level, prices at regional level)
US, California: not included	Add info: No price data available?	No production data available
US, Texas: not included	Add info: No price data available?	No production data available

Estimation results

The Panel Data regressions show significant negative contributions of changes in the share in solar and wind power generation to changes in the power price. On a Monthly basis, these effects are significant at $p<0.05$. The effects remain significant at the 0.05 level after controlling for total power output although the coefficients become slightly smaller. The coefficient for wind is larger than for solar. This is mainly because wind energy also has a larger role in the power mix due to higher load factors. Weekly panel regressions show similar results with the marginal effects being a bit smaller. When controlling for total energy production and only including northern Italy in the regression the coefficient for solar energy becomes insignificant.

The panel data regressions generalise the marginal effects over the countries included. However, due to the differences in the national power systems, significant differences exist between the marginal effects per country. When looking at the weekly and monthly country regressions, we see that for most countries the effect of changes in the share of solar energy on prices are not large enough to be highly significant. We find mildly significant negative effects for Germany, France, Great Britain and one Italian region. For Spain, changes in solar energy also have a significant effect on power prices, but only when they move in tandem with wind energy. In the weekly regressions, we only find a significant effect of solar energy on $p<0.1$ for the northern-central Italy.

Changes in wind energy do have in almost all country regressions a highly significant negative effect on changes in power prices. For France, the share of wind has a very large but not significant effect on power prices. This effect becomes smaller but highly significant when controlling for the share of nuclear energy. This is to be expected because nuclear energy is quite large in France and nuclear energy also has close to zero marginal production costs. For Belgium, we see a similar effect of the share of nuclear power. The regression tables can be found in the appendix.

Modelling power price volatility

In addition to movements in power prices we also attempted to model movements in power price volatility. If the hypothesis that solar and wind power contribute to volatility in power prices, one would expect that a monthly or weekly increase in the average share of solar and wind power in the energy mix would raise the monthly or weekly standard deviation in power prices. Unfortunately, the model as formulated in equation 2 yielded insufficient explanatory power to say anything useful about power price volatility.

Equation 2: Power price volatility model

$$\sigma Power\ price_{it} = \propto_i$$
$$+\beta_1 \Delta Solar\ share_{it}$$
$$+\beta_2 \Delta Wind\ share_{it}$$
$$+\beta_3 (\Delta Solar\ share_{it} * \Delta Wind\ share_{it})$$
$$+ \beta_4 (\Delta Solar\ share_{it} * \Delta Nuclear\ share_{it})$$
$$+\beta_5 (\Delta Wind\ share_{it} * \Delta Nuclear\ share_{it})$$
$$+\beta_6 (\Delta Solar\ share_{it} * \Delta Wind\ share_{it} * \Delta Nuclear\ share_{it})$$
$$+\beta_7 \sigma Total\ power\ production_{it}$$
$$+\beta_8 \sigma CO2\ price_t$$
$$+\beta_9 \sigma Gas\ price_t$$
$$+\beta_{10} \sigma Coal\ price_t$$
$$+\beta_{11} (\sigma CO2\ price_t * \sigma GAS\ price_t)$$
$$+\beta_{12} (\sigma CO2\ price_t * \sigma Coal\ price_t)$$
$$+\beta_{13} (\sigma Gas\ price_t * \sigma Coal\ price_t)$$
$$+\beta_{14} (\sigma CO2\ price_t * \sigma Gas\ price_t * \sigma Coal\ price_t)$$
$$+\epsilon_{it}$$

Where: Monthly or weekly movements in standard deviation are denoted with σ and monthly or weekly movements in the average levels are denoted with Δ.

Although we were not successful in modelling power price volatility it can be argued that the regression results for model *1* are indicative for increased power price volatility. Volatility in the share of solar and wind energy in the power mix contribute to volatility of power prices since there seems to be a negative relationship between movements in the average shares and the averages power price on a monthly and weekly interval. However, without modelling volatility explicitly, it remains difficult to say whether this also results in more volatile power prices.

Annex 1: Summary statistics (weekly data)

All variables are weekly growth rates of 7 day averages

Country name	Var	N	Mean	Sd	p50	min	max
Total	Solar share	1730	3.80864	29.04802	-0.18352	-72.2896	125.3487
	Wind share	1730	10.61026	58.37455	-0.61782	-89.0038	292.2408
	Total	1730	0.563317	9.260881	0.123385	-36.9142	43.58466
	Nuclear	1730	60.35782	150.7002	100	-100	5942.39
	CO2 price	1730	1.103311	4.99086	0.729382	-23.457	17.47877
	Gas price	1730	0.286052	9.023328	-0.43868	-37.9244	60.49587
	Coal price	1730	-0.069	2.562861	0.083297	-9.65215	12.2562
Belgium	Sollar share	161	6.32886	33.30396	1.697302	-60.4428	119.2877
	Wind share	161	15.53372	65.22365	-3.36348	-86.0595	252.4773
	Total production	161	0.475536	7.813773	0.373992	-30.157	39.38906
	Nuclear share	161	0.425456	9.621455	-0.11317	-31.1058	49.3476
France	Sollar share	166	2.793417	20.15669	0.239112	-45.7163	81.35264
	Wind share	166	0.399682	9.290621	0.731301	-22.5859	37.34886
	Total production	166	0.101353	5.533199	-0.53817	-11.5083	18.30206
	Nuclear share	166	0.038698	4.045187	0.089322	-11.7352	10.79682
Germany	Sollar share	121	1.439721	29.49313	-3.839	-66.4726	90.47991
	Wind share	121	12.90343	56.89426	-2.46072	-75.2485	248.6315
	Total production	121	0.782866	8.867998	0.415723	-29.1024	26.39401
	Nuclear share	121	0.702349	13.15365	0.031035	-27.9135	46.24211
Netherlands	Sollar share	155	5.932392	39.23834	-0.29845	-72.2896	111.344
	Wind share	155	10.78098	64.46097	-7.72996	-89.0038	292.2408
	Total production	155	1.38893	12.04834	1.225414	-36.9142	43.58466
	Nuclear share	155	49.66681	480.0184	0.366169	-100	5942.39
Spain	Sollar share	162	5.206923	32.64694	-0.49245	-56.1441	119.3439
	Wind share	162	6.785261	36.70834	4.318134	-58.6929	168.9864
	Total production	162	0.295694	6.41936	0.138053	-15.2862	24.09055
	Nuclear share	162	0.375067	9.321004	-0.00936	-31.1169	36.04259
Italy (Cent.-north)	Solar share	160	3.417061	28.37645	0.244155	-53.5197	125.3487
	Wind share	160	9.618001	61.52234	-0.9275	-80.9382	289.544
	Total production	160	0.474552	8.185579	0.378558	-24.5765	22.19927
Italy (Cent.-south)	Solar share	158	2.240129	29.06772	-0.92038	-61.3764	109.3089
	Wind share	158	13.18808	71.93862	-4.94942	-76.441	291.6869
	Total production	158	1.084323	11.22666	0.728037	-31.5918	40.30133
Italy (north)	Solar share	161	3.475181	30.36924	-1.23984	-65.2387	109.6919
	Wind share	161	11.1069	59.96046	-2.95399	-77.5443	249.7546
	Total production	161	1.082291	10.17988	0.200888	-29.7036	42.68565
Italy (South)	Solar share	163	3.157361	25.461	1.038644	-49.5848	87.84337
	Wind share	163	10.34158	56.88583	-2.7834	-69.3292	216.8262
	Total production	163	0.27062	9.24494	0.211096	-35.1814	32.89787
Italy (Sardina)	Sollar share	160	4.609068	25.34896	0.918757	-45.1553	106.7781
	Wind share	160	10.70137	65.6114	-1.02709	-76.5939	292.0373
	Total production	160	-0.10825	9.815757	-0.46799	-20.7296	37.98157
Italy (Sicily)	Sollar share	163	2.802268	22.52935	0.85501	-59.9428	67.19273
	Wind share	163	16.24658	66.78755	-2.89851	-77.6846	236.1866
	Total production	163	0.459799	10.6909	-0.43099	-22.467	32.31389

Annex 2: Summary statistics (monthly data)

All variables are weekly growth rates of 7 day averages

Country name	Var	N	Mean	Sd	p50	min	max
Total	Solar share	427	8.236258	41.06662	0.62203	-62.7884	168.2937
	Wind share	427	3.611001	34.11553	-0.9068	-67.4249	108.7216
	Total production	427	0.967745	11.66896	-0.19525	-34.0804	69.55595
	Nuclear	427	53.62538	56.91041	100	-83.5044	509.1011
	CO2 price	427	4.698664	9.701058	4.010127	-20.4542	25.15754
	Gas price	427	0.979471	17.99715	-2.92168	-30.2496	49.50029
	Coal price	427	-0.02546	6.952431	-0.35982	-11.9397	22.38676
Belgium	Solar share	34	4.268786	49.82929	-5.1196	-61.007	168.2937
	Wind share	34	7.353617	36.68832	5.739201	-46.4541	106.1626
	Total production	34	1.662067	10.33608	1.78848	-19.8986	38.07468
	Nuclear	34	1.731338	16.44624	1.850936	-40.6189	54.75181
France	Solar share	37	9.503764	39.16879	11.41946	-49.7535	105.4857
	Wind share	37	1.570868	17.6316	1.513564	-28.6952	40.90472
	Total production	37	1.557665	12.52814	-0.6421	-20.5831	42.88209
	Nuclear	37	0.091217	6.165242	0.591099	-15.2385	12.91881
Germany	Solar share	27	-0.36326	48.26719	-14.2851	-62.7884	137.0079
	Wind share	27	4.829859	29.45856	-5.74541	-31.5355	78.16401
	Total production	27	0.763432	8.342412	1.843419	-20.5188	12.6332
	Nuclear	27	0.363009	11.67886	0.726848	-21.8135	27.45591
Great Britain	Solar share	38	7.658989	39.93858	-3.88152	-46.1219	92.08254
	Wind share	38	3.844605	29.3017	-2.21788	-32.652	81.68767
	Total production	38	0.499948	8.006298	0.386086	-17.2003	21.97206
	Nuclear	38	-0.23347	14.52028	0.223341	-26.511	42.48453
Netherlands	Solar share	34	9.253995	57.6261	-9.67583	-57.1256	164.1699
	Wind share	34	3.113463	34.14946	-5.15107	-56.8887	84.36235
	Total production	34	2.256062	13.59799	-0.05622	-19.2904	28.64435
	Nuclear	34	26.85701	105.0522	10.11702	-83.5044	509.1011
Spain	Solar share	38	6.378267	32.16517	5.206719	-48.6523	87.09955
	Wind share	38	3.166977	28.68106	-3.39276	-47.4701	87.75091
	Total production	38	0.6255	9.63522	-1.2919	-13.3848	22.56325
	Nuclear	38	0.571807	13.91984	0.524817	-30.4007	40.13709
Italy (Cent.-north)	Solar share	36	7.052669	33.32568	4.92031	-55.3843	95.37959
	Wind share	36	5.116947	35.90815	0.834026	-52.3016	92.13061
	Total production	36	-0.0077	7.998781	-0.78364	-14.9278	19.32993
Italy (Cent.-south)	Solar share	35	13.06283	43.20388	1.511615	-34.8464	159.9665
	Wind share	35	-0.44149	43.77269	-8.73901	-67.4249	89.61428
	Total production	35	0.707784	11.80048	1.301482	-15.9831	31.30012
Italy (north)	Solar share	38	12.53574	46.64204	6.611612	-60.3951	121.6244
	Wind share	38	5.488357	34.80039	1.694367	-50.7123	81.66448
	Total production	38	2.665893	17.15451	1.727252	-22.1154	69.55595
Italy (South)	Solar share	37	10.22398	35.02646	-1.81675	-43.1933	99.14034
	Wind share	37	2.468012	38.92159	-3.96156	-57.34	108.7216
	Total production	37	0.527272	15.58961	-1.77764	-34.0804	46.75424
Italy (Sardina)	Solar share	38	9.560239	38.07083	8.485488	-52.2011	124.0048
	Wind share	38	5.317544	38.97123	2.876862	-56.5025	84.75074
	Total production	38	-0.1427	10.72675	-0.44382	-23.7377	19.27679
Italy (Sicily)	Solar share	35	7.223741	29.00354	-1.92279	-33.0265	93.55557
	Wind share	35	1.724285	38.10596	-4.90788	-52.6617	90.75868
	Total production	35	0.54605	10.76124	-1.70075	-21.602	19.35536

Annex 3: Weekly regressions

Regressions by country

All variables are weekly growth in 7 day averages

VARIABLES	-1 Germany	-2 France	-3 Netherlands	-4 Belgium	-5 Spain	-6 Italy (north)	-7 Italy (Cent.-north)	-8 Italy (Cent.-south)	-9 Italy (South)	-10 Italy (Sicily)	-11 Italy (Sardina)
Delta CO2 price	0.434	0.426**	0.568***	0.258	0.0119	0.0544	0.0207	0.0426	0.126	-0.183	0.113
	-0.283	-0.179	-0.15	-0.217	-0.192	-0.129	-0.153	-0.122	-0.161	-0.248	-0.172
Delta Coal price	-0.0121	0.483	0.408	1.106	0.0838	0.228	-0.0694	-0.286	-0.379	0.185	-0.0263
	-0.716	-0.383	-0.26	-0.714	-0.539	-0.325	-0.372	-0.46	-0.43	-0.393	-0.603
Delta CO2 price * Delta Coal price	0.193*	-0.0319	0.0325	0.0374	0.159*	-0.0621	-0.0517	-0.0308	-0.0224	-0.114	-0.0721
	-0.114	-0.075	-0.056	-0.0967	-0.0863	-0.0548	-0.075	-0.063	-0.0668	-0.0842	-0.0961
Delta Gas price	0.258	0.365***	0.547***	0.640***	0.291**	0.426***	0.559***	0.506***	0.441***	0.349*	0.438**
	-0.179	-0.113	-0.076	-0.127	-0.137	-0.105	-0.123	-0.0967	-0.149	-0.181	-0.188
Delta CO2 price * Delta Gas price	0.0426	0.0638**	0.0400*	0.0388	-0.0504	0.00898	0.00161	0.00985	0.0252	-0.00643	0.00724
	-0.0433	-0.0262	-0.0212	-0.0383	-0.0352	-0.0238	-0.0283	-0.0245	-0.0333	-0.0411	-0.0454
Delta Coal price * Delta Gas price	-0.138	0.0271	0.00381	-0.0781	-0.0998	0.0104	-0.022	-0.048	-0.0234	0.0241	-0.0129
	-0.126	-0.0681	-0.0481	-0.108	-0.0976	-0.0582	-0.0729	-0.0753	-0.078	-0.071	-0.11
Delta CO2 price * Delta Coal price * Delta Gas price	0.0107	0.00386	0.000408	0.00432	-0.00964	0.000995	-0.00295	0.00167	0.00996	-0.0167	0.00786
	-0.0171	-0.0127	-0.0096	-0.0194	-0.0184	-0.0109	-0.0156	-0.0131	-0.0128	-0.0158	-0.0219
Delta solar share	-0.0628	-0.0317	-0.0132	-0.00282	-0.0183	-0.011	-0.0442*	0.00896	-0.0565	-0.0452	-0.0512*
	-0.0439	-0.0444	-0.0156	-0.0284	-0.0249	-0.0175	-0.0239	-0.0226	-0.0372	-0.0523	-0.0298
Delta wind share	-0.249***	-0.979***	-0.0738***	-0.178***	-0.214***	-0.0254**	-0.0356***	-0.0392***	-0.115***	-0.145***	-0.0512***
	-0.0386	-0.14	-0.0102	-0.0202	-0.0389	-0.0111	-0.0112	-0.00913	-0.0177	-0.0148	-0.0144
Delta solar share * Delta wind share	-0.00124	-0.00378	-0.000246	-0.000566	0.000703	9.95E-05	3.08E-05	0.000433	-3.33E-05	-0.00280***	-0.000773*
	-0.000989	-0.00883	-0.000235	-0.000435	-0.000735	-0.000334	-0.000515	-0.000339	-0.00051	-0.000853	-0.000402
Delta nuclear share	0.0653	-3.500***	0.00453	-0.610***	0.0511						
	-0.145	-0.341	-0.0126	-0.117	-0.152						
Delta solar share * Delta nuclear share	-0.000704	-0.00479	-0.000854*	-0.00455	-0.00126						
	-0.0022	-0.02	-0.000477	-0.00397	-0.00391						
Delta wind share * Delta nuclear share	-9.29E-05	0.00834	8.95E-05	-0.00744***	0.00138						
	-0.00213	-0.0215	-0.000213	-0.00241	-0.0032						
Delta solar share * Delta wind share * Delta nuclear share	-3.87E-05	-0.000566	1.05E-05	-0.000103*	-0.000210**						
	-5.38E-05	-0.000964	-7.71E-06	-6.00E-05	-0.000105						
Detla total production	0.414*	0.644***	0.226***	0.374***	0.606***	0.563***	0.285***	0.341***	0.139	0.498***	-0.212*
	-0.249	-0.232	-0.0515	-0.123	-0.181	-0.0611	-0.102	-0.0641	-0.14	-0.115	-0.117
Constant	2.318	1.491	0.863	2.120*	1.571	0.671	1.653**	1.300*	1.938**	2.124*	1.066
	-1.508	-0.928	-0.65	-1.2	-1.062	-0.701	-0.804	-0.667	-0.872	-1.211	-0.886
Observations	121	166	155	161	162	161	160	158	163	163	160
R-squared	0.523	0.672	0.624	0.563	0.412	0.522	0.314	0.436	0.365	0.383	0.223

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Weekly Panel regressions

All variables are weekly growth in 7 day averages

VARIABLES	-1 all countries	-2 all countries	-3 ex south and central Italy	-4 ex south and central Italy
Delta CO2 price	0.147**	0.139**	0.223**	0.235**
	-0.0471	-0.0538	-0.0714	-0.0777
Delta Coal price	-0.0165	0.0182	0.123	0.172
	-0.107	-0.109	-0.174	-0.181
Delta CO2 price * Delta Coal price	0.0036	0.00178	0.0451	0.0431
	-0.0237	-0.0243	-0.0365	-0.0406
Delta Gas price	0.478***	0.476***	0.500***	0.487***
	-0.0344	-0.0354	-0.0554	-0.0611
Delta CO2 price * Delta Gas price	0.0156*	0.0132	0.0235	0.0226
	-0.00857	-0.00865	-0.0151	-0.014
Delta Coal price * Delta Gas price	-0.0466***	-0.0409***	-0.0663**	-0.0548*
	-0.0129	-0.0129	-0.0206	-0.0231
Delta CO2 price * Delta Coal price * Delta Gas price	0.0028	0.0013	0.00269	0.00171
	-0.00214	-0.00228	-0.00304	-0.00262
Delta solar share	-0.0375**	-0.0242*	-0.0345**	-0.0174
	-0.0128	-0.0109	-0.0127	-0.0105
Delta wind share	-0.141***	-0.143***	-0.140***	-0.142**
	-0.0256	-0.0328	-0.0271	-0.0376
Delta solar share * Delta wind share	-0.000497*	-0.000458*	-0.000432	-0.000408
	-0.000242	-0.000252	-0.000269	-0.000284
Delta nuclear share	-0.0306	-0.0335	-0.0368	-0.0386
	-0.0185	-0.0224	-0.0229	-0.0285
Delta solar share * Delta nuclear share	-0.000166	-1.55E-05	-0.000247	-0.000203
	-0.00018	-0.000208	-0.000259	-0.000273
Delta wind share * Delta nuclear share	0.000677**	0.000687*	0.000725*	0.000889
	-0.000283	-0.000357	-0.000341	-0.000456
Delta solar share * Delta wind share * Delta nuclear share	3.27E-06	1.87E-06	8.73E-06	2.57E-06
	-4.47E-06	-4.50E-06	-4.56E-06	-4.59E-06
Detla total production		0.255**		0.353*
		-0.0888		-0.172
Constant	3.610**	3.570**	2.488**	2.179**
	-1.139	-1.367	-0.682	-0.763
Observations	1,730	1,730	926	926
R-squared	0.28	0.306	0.311	0.35
Number of country_id	11	11	6	6

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Annex 4: Monthly regressions

Regressions by country

All variables are monthly growth in 28 day averages

VARIABLES	-1 Germany	-2 France	-3 Netherlands	-4 Belgium	-5 Spain	-6 Great Britain	-7 Italy (north)	-8 Italy (Cent.-north)	-9 Italy (Cent.-south)	-10 Italy (South)	-11 Italy (Sicily)	-12 Italy (Sardina)
Delta CO2 price	0.646**	0.388	0.742**	0.45	0.313	0.415**	0.649**	0.521	0.356	0.388	0.637	0.63
	-0.277	-0.238	-0.341	-0.322	-0.707	-0.177	-0.277	-0.33	-0.248	-0.293	-0.624	-0.414
Delta Coal price	-0.0867	0.821*	-0.335	0.122	1.205	0.176	0.736**	0.885*	0.143	0.661*	0.878	1.013*
	-0.686	-0.397	-0.298	-0.484	-0.778	-0.404	-0.34	-0.494	-0.34	-0.375	-0.735	-0.534
Detla CO2 price * Delta Coal price	0.0351	-0.0676*	0.0467	0.00377	-0.0698	0.00727	0.0175	-0.0152	0.00611	-0.0353	-0.0144	-0.000643
	-0.0434	-0.0387	-0.0461	-0.0558	-0.113	-0.0442	-0.0446	-0.0568	-0.0487	-0.053	-0.102	-0.0804
Delta Gas price	0.136	0.322**	0.447***	0.489***	0.062	0.465***	0.178	0.19	0.275**	0.306***	0.0754	0.17
	-0.0986	-0.118	-0.074	-0.142	-0.256	-0.0502	-0.124	-0.16	-0.109	-0.0631	-0.167	-0.158
Detla CO2 price * Delta Gas price	0.0717**	0.0324*	0.0390**	0.0628**	0.0602	0.0338	0.0375**	0.0512**	0.0349**	0.0554***	0.00832	0.0375
	-0.0274	-0.017	-0.0175	-0.0272	-0.0407	-0.0215	-0.018	-0.0228	-0.0157	-0.0175	-0.0332	-0.0253
Detla Coal price * Delta Gas price	-0.0111	-0.0192	0.000527	0.00592	0.0663	0.0383*	-0.0102	0.0149	-0.00451	0.0284*	0.0345	0.0132
	-0.039	-0.0209	-0.0127	-0.0336	-0.0395	-0.0216	-0.0147	-0.0193	-0.0161	-0.0151	-0.027	-0.0205
Detla CO2 price * Delta Coal price * Delta Gas price	-0.00333	0.000141	-0.00362	-0.00492	-0.00683	-0.00253	-0.00482*	-0.00471	-0.00266	-0.00418	-0.00701	-0.00601
	-0.00521	-0.00244	-0.0032	-0.00381	-0.00762	-0.002	-0.00248	-0.00315	-0.00251	-0.00285	-0.00578	-0.00361
Delta total production	0.783*	-0.0497	0.194	0.3	0.610*	-0.319	0.390***	0.481**	0.462***	0.233*	0.293	-0.177
	-0.397	-0.165	-0.194	-0.209	-0.324	-0.328	-0.0992	-0.232	-0.137	-0.121	-0.257	-0.256
Delta solar share	-0.0821*	-0.106*	-0.0542	-0.0635	-0.0715	-0.0984*	-0.0266	-0.0483	-0.00207	0.0161	-0.269**	-0.0496
	-0.0444	-0.0582	-0.0511	-0.0488	-0.0811	-0.0561	-0.0335	-0.0673	-0.023	-0.037	-0.112	-0.0683
Delta wind share	-0.524***	-1.094***	0.0091	-0.204***	-0.379***	-0.132***	0.0237	-0.0852*	-0.0894**	-0.120*	-0.225**	-0.102
	-0.0649	-0.144	-0.0821	-0.0599	-0.126	-0.0465	-0.061	-0.0474	-0.0387	-0.0641	-0.0978	-0.0861
Detla solar share * Delta wind share	-0.00111	-0.00557	-0.0009	-0.000313	-0.00652*	-0.000342	-3.63E-05	-0.000595	-0.000623	-0.00175	-0.00563**	-0.00184
	-0.00108	-0.00417	-0.0013	-0.0016	-0.00337	-0.00185	-0.00114	-0.00141	-0.000488	-0.00113	-0.00271	-0.00143
Delta nuclear share	0.165	-3.918***	-0.0412	-0.289	0.0725	-0.245*						
	-0.257	-0.495	-0.0258	-0.216	-0.323	-0.135						
Detla solar share * Delta nuclear share	0.0061	0.00484	-0.000135	-0.00123	0.00135	0.00249						
	-0.00823	-0.0129	-0.000975	-0.00448	-0.00677	-0.00283						
Detla wind share * Delta nuclear share	0.0167	-0.0497***	-0.00355**	0.00692	0.0262**	0.00201						
	-0.011	-0.017	-0.00152	-0.00653	-0.0094	-0.00392						
Detla solar share * Delta wind share * Delta nuclear share	0.000454*	-0.00154**	9.52E-05	0.000382**	0.000418	0.00011						
	-0.000252	-0.000562	-7.66E-05	-0.000181	-0.000255	-0.000125						
Constant	2.739	-0.0256	-0.0973	2.02	-2.515	-2.540*	-1.387	-1.688	-0.611	-2.441	-0.538	-1.876
	-2.212	-2.052	-2.434	-2.422	-4.893	-1.369	-2.567	-2.659	-1.831	-1.721	-3.891	-3.146
Observations	27	37	34	34	38	38	38	36	35	37	35	38
R-squared	0.927	0.923	0.842	0.812	0.68	0.863	0.73	0.651	0.782	0.682	0.549	0.542

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Monthly Panel regressions

All variables are monthly growth in 28 day averages

VARIABLES	-1 all countries	-2 all countries	-3 ex south and central Italy	-4 ex south and central Italy
Delta CO2 price	0.549***	0.532***	0.541***	0.552***
	-0.043	-0.0497	-0.0718	-0.0761
Delta Coal price	0.553***	0.485***	0.465**	0.366*
	-0.114	-0.124	-0.183	-0.178
Detla CO2 price * Delta Coal price	0.00538	0.00507	0.00815	0.0105
	-0.00869	-0.0105	-0.0144	-0.0158
Delta Gas price	0.289***	0.305***	0.349***	0.356***
	-0.0452	-0.0437	-0.0645	-0.0645
Detla CO2 price * Delta Gas price	0.0519***	0.0507***	0.0642***	0.0609***
	-0.00652	-0.00668	-0.00883	-0.00984
Detla Coal price * Delta Gas price	0.0141**	0.0134*	0.0164	0.0141
	-0.00638	-0.00678	-0.0111	-0.0116
Detla CO2 price * Delta Coal price * Delta Gas price	-0.00516***	-0.00491***	-0.00580***	-0.00535***
	-0.000561	-0.000558	-0.000855	-0.000827
Delta total production		0.208***		0.264**
		-0.0512		-0.0965
Delta solar share	-0.0692***	-0.0439***	-0.0642***	-0.0344**
	-0.0166	-0.0134	-0.0163	-0.011
Delta wind share	-0.185**	-0.169**	-0.183**	-0.163**
	-0.0598	-0.0649	-0.0603	-0.0653
Detla solar share * Delta wind share	0.00047	0.000182	0.000641	0.000157
	-0.000497	-0.000485	-0.000549	-0.00055
Delta nuclear share	-0.0304	-0.0299	-0.032	-0.0324*
	-0.0211	-0.0183	-0.0184	-0.0153
Detla solar share * Delta nuclear share	0.000257	0.000229	9.31E-05	-6.60E-05
	-0.000243	-0.000243	-0.000395	-0.000295
Detla wind share * Delta nuclear share	0.000523	0.000449	0.000537	0.000991
	-0.000692	-0.000759	-0.00113	-0.00136
Detla solar share * Delta wind share * Delta nuclear share	-1.61e-05**	-1.08E-05	-8.42E-06	4.77E-06
	-5.95E-06	-6.27E-06	-1.29E-05	-8.08E-06
Constant	0.859	0.46	0.232	-0.512
	-1.263	-1.101	-0.571	-0.458
Observations	427	427	246	246
R-squared	0.522	0.539	0.54	0.559
Number of country_id	12	12	7	7
Country FE	YES	YES	YES	YES

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

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