Effectiveness of Climate Policies: Carbon Pricing vs. Subsidizing Renewables

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Introduction

Anthropogenic climate change poses a fundamental threat to humankind

- In economic terms, greenhouse gas (GHG) emissions can be viewed as a market failure, which has to be corrected (Stern, 2007)
- Economists agree that pricing the externality is a **first-best** policy, while **second-best** options (e.g. subsidization of renewables) are popular among policymakers

Research goal:

- **We assess the effectiveness of climate policies** (i.e. carbon pricing & subsidization of wind and solar power) in DE's & UK's electricity sectors

DE & UK follow different climate strategies:

- Despite vast subsidization of wind & solar power (€34 bn. in 2017), DE will dramatically fail its climate goals set for 2020
- UK spends much less on renewables but has a high price on emissions from power sector (carbon price floor, CPF) → Emissions from power sector declined by approximately 55% within only 5 years

Our paper in a nutshell

Our paper examines **effectiveness of CO_2 abatement policies** in UK & DE

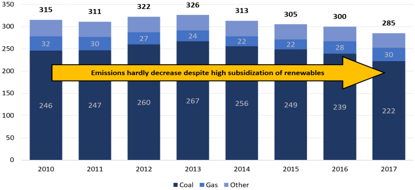
- Focus on electricity sector (most pollutive sector in DE, UK & globally)
- We explain why DE failed and the UK succeeded in reducing emissions
- We assess which policies are cost-effective in reducing emissions (using directly associable costs of the various policies)
- We model daily CO_2 emissions from all coal & gas power plants
- Heckman selection model allows for taking UK plant exits into account (extensive margin)

Main results:

- Carbon pricing is the most cost-effective climate policy
- Subsidization of wind is preferable to solar power

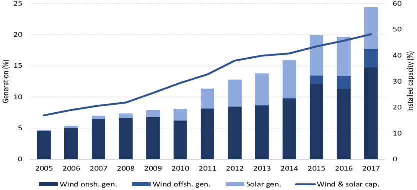
Germany

Emissions from power sector ($MtCO_2$), DE



Emissions hardly decrease despite high subsidization of renewables

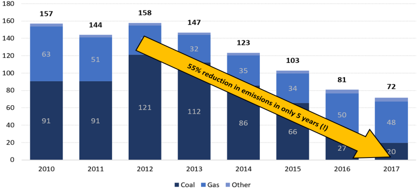
Wind & solar power (%), DE



→ **Hardly any decline in emissions despite high share of RES**

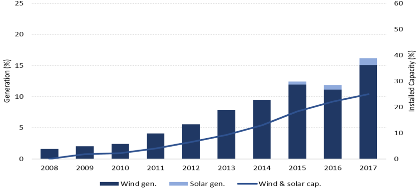
United Kingdom

Emissions from power sector ($MtCO_2$), UK



55% reduction in emissions in only 5 years (!)

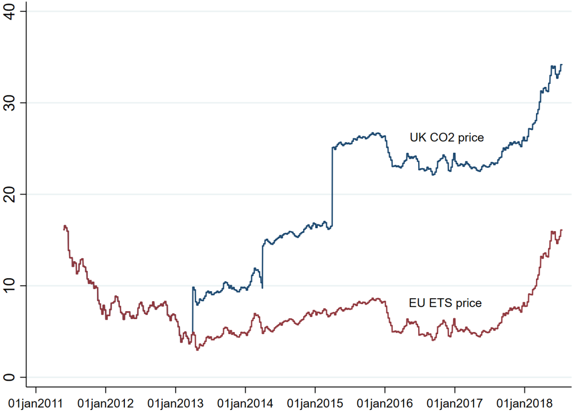
Wind & solar power (%), UK



→ **Strong decline in emissions despite low share of RES**

But why?

UK introduced a significant unilateral carbon tax



DE carbon price = EU ETS price

UK carbon price = EU ETS price + CPS:

Apr 1, 2013–Mar 31, 2014: CPS = £4.94 (= €5.84)
Apr 1, 2014–Mar 31, 2015: CPS = £9.55 (= €11.46)
Apr 1, 2015–Mar 31, 2021: CPS = £18.08 (= €24.63)

Environmental Policy in Theory and Practice

Theory:

- Carbon pricing is a **first-best solution**: internalization of externality based on market incentives → leads to cost-efficient emissions abatement (Pigou 1932)
- Economists have long agreed that a direct price on a pollution externality is superior to alternative indirect measures, such as subsidies (e.g. Holland et al. 2016 AER)
- Other climate policies (e.g. subsidization of RES) are only **second-best solutions** (no market-based incentives, less cost-efficient)

Practice:

- **Political economy** hinders effective climate policy: "policy failure sits alongside market failure" (Newberry et al 2018 Energy J)
- Political fear of negative consequences of adequate price on emissions
- Implementation of (unilateral, uncoordinated) second-best measures has become popular
- Most countries (Germany) dramatically fail their climate targets (Bundesrechnungshof 2018)

Comparison of Climate Policies

EU: ineffectively low EU ETS carbon price

- EU promised in Paris Climate Agreement to reduce greenhouse gas (GHG) emissions by at least 40% until 2030 compared to 1990 level
- EU ETS largest emissions cap-&-trade program worldwide
- But until recently, carbon price has been ineffectively low

DE: vast subsidization of RES

- DE promised to reduce GHG by 55% until 2030 and by 80%–95% until 2050 (BMUB 2016 "Klimaschutzplan 2050")
- Road map: vast subsidization of wind & solar power → Target: 80% RES in national electricity supply by 2050
- DE affords the highest per-capita subsidies for RES in the world

UK: significant unilateral carbon pricing

- UK supports ineffectively low EU ETS price with a significant top-up tax
- High carbon price already induced exits of coal plants

Coal vs. Gas

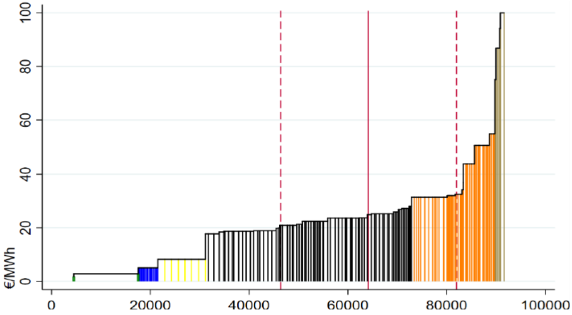
Subsidized RES (wind & solar) mainly replace gas, whereas coal (esp. lignite) remains in the market Liebensteiner & Wrienz (2019, EnergyEcon)

Gas is 'cleaner' than coal

- New gas power plants emits about 50%–60% less carbon dioxide per MWh compared to a typical new coal plant (USDE 2013; EIA 2018)
- With increasing carbon price, marginal costs of (some forms of) coal increase relative to marginal costs of gas
- At a "high-enough carbon price", coal and gas switch their positions in the merit order
- This "**fuel switch**" would drastically reduce emissions (Wilson & Staffell 2018 NatureEnergy)

Figure 4: Merit order for different carbon prices, DE

(a) Merit order at a carbon price of €5



(b) Merit order at a carbon price of €15

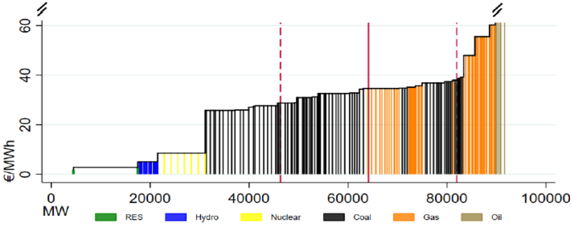
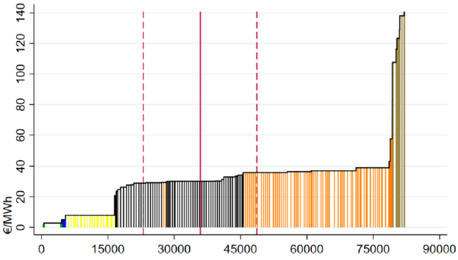
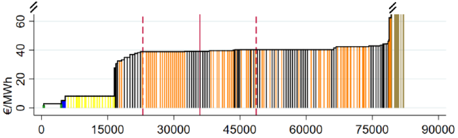


Figure 5: Merit order for different carbon prices, UK

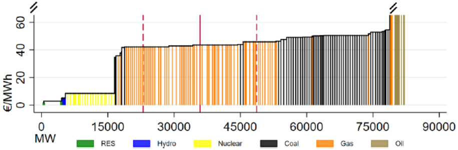
(a) Merit order at a carbon price of €5



(b) Merit order at a carbon price of €15



(c) Merit order at a carbon price of €25



So, a high-enough carbon price replaces coal ...

25/04/2017 at 2:58pm Tom Grimwood

Britain's day without coal

Last week saw a major milestone in the decarbonisation of the UK's power sector, as Emma Tribe and David Thomas from Elexon explain.

utilityweek.co.uk

Literature

Related literature:

- One strand analyzes only second-best climate policies (wind & solar) with respect to their abatement effects (Abrell et al. 2019 JPubE; Cullen 2013 AEJ:EP; Novan 2015 AEJ:EP)
- Another strand investigates effects of relative gas-to-coal price to predict effect of carbon pricing on emissions (Cullen & Mansur 2017 AEJ:EP; Fell and Kaffine 2018 AEJ:EP)

Our main features:

- So far, no paper which analyzes effectiveness of both *carbon pricing & renewables*
- We draw conclusions from a *high* carbon price (as observed in the UK) and compare to low carbon price (DE)
- Our analysis is richer in some dimensions (highly non-linear model, rich set of fixed effects and dynamic effects, analysis at plant level)

Model: Heckman 2-step method

$$y_{p,n,t,c} = f(P, W, S, D, \vec{X})$$

Daily emissions of plant p in country $c = [DE, UK]$ using technology $n = [coal, gas]$ are a function of the carbon price (P), wind (W), solar (S), load (D), and control variables ($\vec{X}$; such as cost ratio $CR = P_{coal,t}/P_{gas,t}$; operating state $OS_{t-24} = 0/1$; day-of-week, monthly & yearly fixed effects)

Heckman model:

- We observe permanent plant exits in the UK → With OLS, exits and zero-production periods cannot be captured adequately
- We apply Heckman two-step model to estimate **full effect** of P on emissions, which is composed of *intensive* (generation conditional on operating) and *extensive* (on/off decision) margin response

Step 1: selection equation (probit) estimates probability of operating (having positive emissions) ($z_{p,c,n,t} = 1$ if $y_{p,c,n,t} > 0$ and $z_{p,c,n,t} = 0$ if $y_{p,c,n,t} = 0$). Then, obtain the inverse Mill's ratio as $\hat{\lambda}_{p,c,n,t} = \phi(.)/\Phi(.)$, $\phi =$ normal pdf, Φ $=$ cdf.

Step 2: run outcome equation, corrected for selection by adding $\hat{\lambda}$, via OLS. Full effect: $\mathbb{E}[y_{p,c,n,t}|\mathbf{X}_{p,c,n,t}, \mathbf{V}_{p,c,n,t}] = \Phi(\mathbf{V}_{p,c,n,t}\alpha)[\mathbf{X}_{p,c,n,t}\beta + \rho\lambda_{p,c,n,t}]$

Heckman method: 1st stage

$$
\begin{aligned}
z_{p,c,n,t} = & \sum_{i=1}^{2} \alpha_{Pi} P_{t,c}^{i} + \alpha_{PW} P_{t,c} W_{t,c} + \alpha_{PS} P_{t,c} S_{t,c} + \alpha_{PL} P_{t,c} L_{t,c} + \alpha_{PCR} P_{t,c} CR_{t,c} + \\
& \sum_{i=1}^{3} \alpha_{Wi} W_{t,c}^{i} + \sum_{i=1}^{3} \alpha_{Si} S_{t,c}^{i} + \sum_{i=1}^{3} \alpha_{Li} L_{t,c}^{i} + \sum_{i=1}^{3} \alpha_{CRi} CR_{t,c}^{i} + \\
& \sum_{i=1}^{3} \sum_{j=1}^{3} \alpha_{WiLj} W_{t,c}^{i} L_{t,c}^{j} + \sum_{i=1}^{3} \sum_{j=1}^{3} \alpha_{SiDj} S_{t,c}^{i} L_{t,c}^{j} + \sum_{i=1}^{3} \sum_{j=1}^{3} \alpha_{WiSj} W_{t,c}^{i} S_{t,c}^{j} + \\
& \sum_{i=1}^{5} \alpha_{\Delta W t-i} \Delta W_{t-i,c} + \sum_{i=1}^{5} \alpha_{\Delta S t-i} \Delta S_{t-i,c} + \delta_p D_p + \delta_t D_t + \\
& \sum_{i=1}^{5} \alpha_{Lt-i} L_{t-i,c} + u_{p,c,n,t}. \qquad (1)
\end{aligned}
$$

Exclusion restriction rests on inclusion of five-day lags of load ($\sum_{i=1}^{5} L_{t-i,c}$; Fell & Kaffine 2018 AEJ:EcPol) as well as on different moments of variables included in selection and outcome regressions

Heckman method: 2nd stage

$$\begin{aligned}
y_{p,c,n,t} = & \sum_{i=1}^{2} \beta_{Pi} P_{t,c}^{i} + \beta_{PW} P_{t,c} W_{t,c} + \beta_{PS} P_{t,c} S_{t,c} + \beta_{PL} P_{t,c} L_{t,c} + \beta_{PCR} P_{t,c} CR_{t,c} + \\
& \sum_{i=1}^{3} \beta_{Wi} W_{t,c}^{i} + \sum_{i=1}^{3} \beta_{Si} S_{t,c}^{i} + \sum_{i=1}^{3} \beta_{Li} L_{t,c}^{i} + \sum_{i=1}^{3} \beta_{CRi} CR_{t,c}^{i} + \\
& \sum_{i=1}^{3} \sum_{j=1}^{3} \beta_{WiLj} W_{t,c}^{i} L_{t,c}^{j} + \sum_{i=1}^{3} \sum_{j=1}^{3} \beta_{SiDj} S_{t,c}^{i} L_{t,c}^{j} + \sum_{i=1}^{3} \sum_{j=1}^{3} \beta_{WiSj} W_{t,c}^{i} S_{t,c}^{j} + \\
& \sum_{i=1}^{5} \beta_{\Delta Wt-i} \Delta W_{t-i,c} + \sum_{i=1}^{5} \beta_{\Delta St-i} \Delta S_{t-i,c} + \delta_p D_p + \delta_t D_t + \\
& \rho \hat{\lambda}_{p,c,n,t} + \epsilon_{p,c,n,t}. \qquad (2)
\end{aligned}$$

Full effect: $\mathbb{E}[y_{p,c,n,t} | \mathbf{X}_{p,c,n,t}, \mathbf{V}_{p,c,n,t}] = \Phi(\mathbf{V}_{p,c,n,t}\alpha)[\mathbf{X}_{p,c,n,t}\beta + \rho\lambda_{p,c,n,t}]$

Data

We compute **daily emissions** of coal and gas plants in DE & UK:

- Daily electricity generation data at the power plant level: EEX Transparency Platform (DE), PLATTS PowerVision (UK)
- Power plant characteristics (capacity, construction date, turbine type, fuel type): PLATTS PowerVision
- Emission and efficiency factors by plant vintage: APG & external sources
- In aggregate, our calculated emissions fit official statistics quite well

Sample periods

- UK: long sample (2011/05/27/0h – 2018/07/15/23h) including time before unilateral tax; but no data on solar feed-in (i.e. negligible share)
- DE: shorter sample (2017/01/01/0h – 2018/06/29/23h)

UK: long-run coal plant exits

- In UK, we observe plant exits: 33 plant units (= 14,250 MW) became inactive, while 30 units (= 13,885 MW) are still active

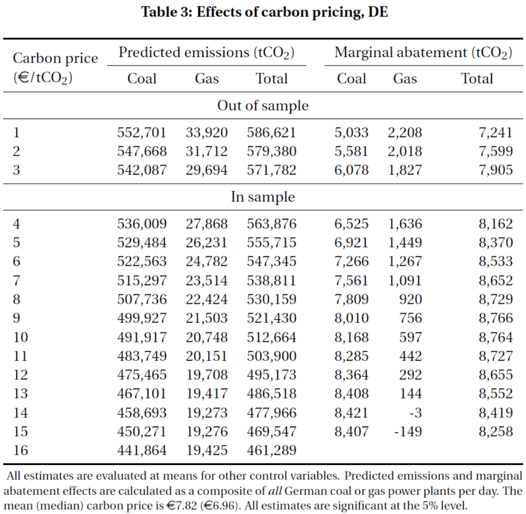


Table 3: Effects of carbon pricing, DE

Carbon price (€/tCO_2)	Predicted emissions (tCO_2)			Marginal abatement (tCO_2)		
	Coal	Gas	Total	Coal	Gas	Total
Out of sample						
1	552,701	33,920	586,621	5,033	2,208	7,241
2	547,668	31,712	579,380	5,581	2,018	7,599
3	542,087	29,694	571,782	6,078	1,827	7,905
In sample						
4	536,009	27,868	563,876	6,525	1,636	8,162
5	529,484	26,231	555,715	6,921	1,449	8,370
6	522,563	24,782	547,345	7,266	1,267	8,533
7	515,297	23,514	538,811	7,561	1,091	8,652
8	507,736	22,424	530,159	7,809	920	8,729
9	499,927	21,503	521,430	8,010	756	8,766
10	491,917	20,748	512,664	8,168	597	8,764
11	483,749	20,151	503,900	8,285	442	8,727
12	475,465	19,708	495,173	8,364	292	8,655
13	467,101	19,417	486,518	8,408	144	8,552
14	458,693	19,273	477,966	8,421	-3	8,419
15	450,271	19,276	469,547	8,407	-149	8,258
16	441,864	19,425	461,289			

All estimates are evaluated at means for other control variables. Predicted emissions and marginal abatement effects are calculated as a composite of *all* German coal or gas power plants per day. The mean (median) carbon price is €7.82 (€6.96). All estimates are significant at the 5% level.

- At mean of €8/tCO2, 9.6% emissions are offset; at €16/tCO2 **21%** are offset
- Higher carbon price becomes successively **more effective** in reducing coal emissions
- With higher carbon price, gas produces more to fill gap from missing coal; negative abatement can be explained by **fuel switching** (gas into merit order); positive abatement mainly through imports

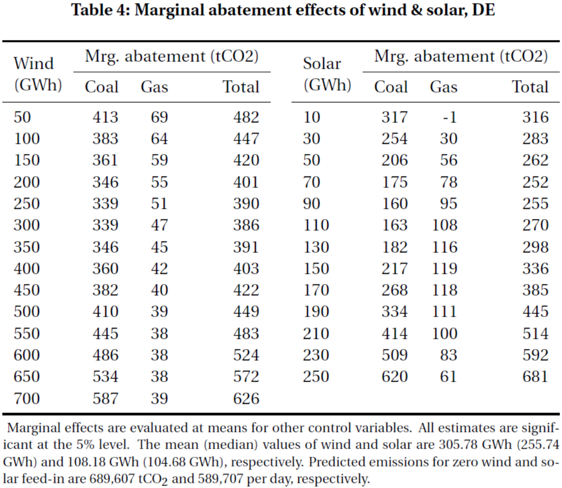


Table 4: Marginal abatement effects of wind & solar, DE

Wind (GWh)	Mrg. abatement (tCO2)			Solar (GWh)	Mrg. abatement (tCO2)		
	Coal	Gas	Total		Coal	Gas	Total
50	413	69	482	10	317	-1	316
100	383	64	447	30	254	30	283
150	361	59	420	50	206	56	262
200	346	55	401	70	175	78	252
250	339	51	390	90	160	95	255
300	339	47	386	110	163	108	270
350	346	45	391	130	182	116	298
400	360	42	403	150	217	119	336
450	382	40	422	170	268	118	385
500	410	39	449	190	334	111	445
550	445	38	483	210	414	100	514
600	486	38	524	230	509	83	592
650	534	38	572	250	620	61	681
700	587	39	626				

Marginal effects are evaluated at means for other control variables. All estimates are significant at the 5% level. The mean (median) values of wind and solar are 305.78 GWh (255.74 GWh) and 108.18 GWh (104.68 GWh), respectively. Predicted emissions for zero wind and solar feed-in are 689,607 tCO_2 and 589,707 per day, respectively.

- For higher levels of wind and solar feed-in, marginal abatement modestly declines then increases
- At mean wind feed-in (300 GWh), a marginal increase by one GWh replaces 386 tCO2 per day (mostly coal emissions), and **18%** of total daily emissions
- Average solar (110 GWh) marginally replaces 270 tCO2 and **6%** of total daily emissions

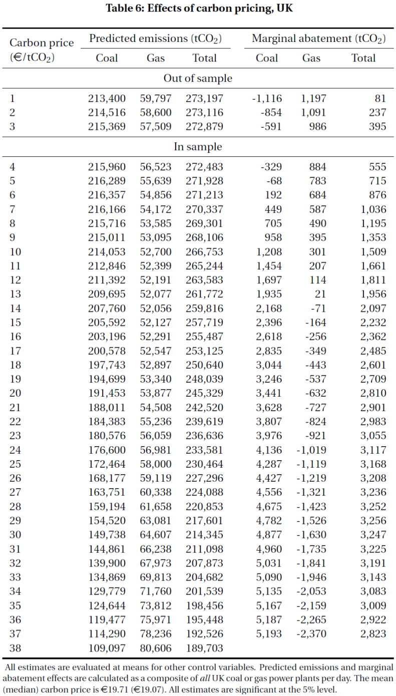


Table 6: Effects of carbon pricing, UK

Carbon price (€/tCO$_2$)	Predicted emissions (tCO$_2$)			Marginal abatement (tCO$_2$)		
	Coal	Gas	Total	Coal	Gas	Total
Out of sample						
1	213,400	59,797	273,197	-1,116	1,197	81
2	214,516	58,600	273,116	-854	1,091	237
3	215,369	57,509	272,879	-591	986	395
In sample						
4	215,960	56,523	272,483	-329	884	555
5	216,289	55,639	271,928	-68	783	715
6	216,357	54,856	271,213	192	684	876
7	216,166	54,172	270,337	449	587	1,036
8	215,716	53,585	269,301	705	490	1,195
9	215,011	53,095	268,106	958	395	1,353
10	214,053	52,700	266,753	1,208	301	1,509
11	212,846	52,399	265,244	1,454	207	1,661
12	211,392	52,191	263,583	1,697	114	1,811
13	209,695	52,077	261,772	1,935	21	1,956
14	207,760	52,056	259,816	2,168	-71	2,097
15	205,592	52,127	257,719	2,396	-164	2,232
16	203,196	52,291	255,487	2,618	-256	2,362
17	200,578	52,547	253,125	2,835	-349	2,485
18	197,743	52,897	250,640	3,044	-443	2,601
19	194,699	53,340	248,039	3,246	-537	2,709
20	191,453	53,877	245,329	3,441	-632	2,810
21	188,011	54,508	242,520	3,628	-727	2,901
22	184,383	55,236	239,619	3,807	-824	2,983
23	180,576	56,059	236,636	3,976	-921	3,055
24	176,600	56,981	233,581	4,136	-1,019	3,117
25	172,464	58,000	230,464	4,287	-1,119	3,168
26	168,177	59,119	227,296	4,427	-1,219	3,208
27	163,751	60,338	224,088	4,556	-1,321	3,236
28	159,194	61,658	220,853	4,675	-1,423	3,252
29	154,520	63,081	217,601	4,782	-1,526	3,256
30	149,738	64,607	214,345	4,877	-1,630	3,247
31	144,861	66,238	211,098	4,960	-1,735	3,225
32	139,900	67,973	207,873	5,031	-1,841	3,191
33	134,869	69,813	204,682	5,090	-1,946	3,143
34	129,779	71,760	201,539	5,135	-2,053	3,083
35	124,644	73,812	198,456	5,167	-2,159	3,009
36	119,477	75,971	195,448	5,187	-2,265	2,922
37	114,290	78,236	192,526	5,193	-2,370	2,823
38	109,097	80,606	189,703			

All estimates are evaluated at means for other control variables. Predicted emissions and marginal abatement effects are calculated as a composite of *all* UK coal or gas power plants per day. The mean (median) carbon price is €19.71 (€19.07). All estimates are significant at the 5% level.

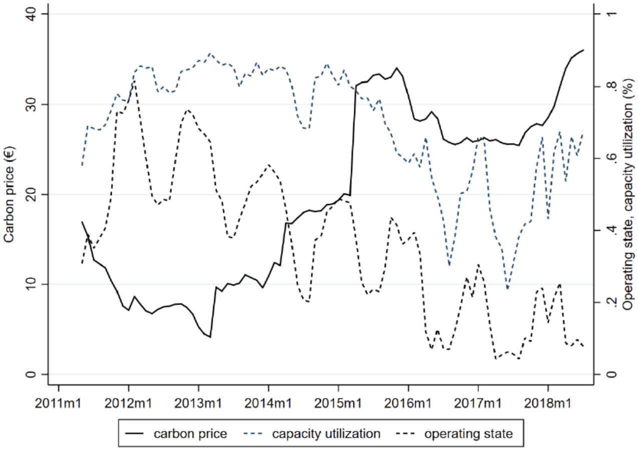
- Dramatically increasing marginal abatement up to €29; stays significant thereafter
- At €36/tCO2, **31%** of total emissions (and 55% of coal emissions) are replaced

Table A5: Probability of producing conditional on the carbon price, UK

Carbon price (€)	Coal plants	Gas plants
5	38.5%	34.8%
7	37.5%	34.7%
9	36.5%	34.7%
11	35.3%	34.9%
13	34.1%	35.3%
15	32.8%	35.9%
17	31.4%	36.7%
19	29.9%	37.7%
21	28.4%	38.9%
23	26.8%	40.3%
25	25.2%	41.9%
27	23.6%	43.7%
29	21.9%	45.7%
31	20.3%	47.9%
33	18.6%	50.4%
35	17.0%	53.0%
37	15.3%	55.9%

This Table gives the probability of producing electricity from coal- or gas-fired power plants based on probit estimates of eq. 2 for the UK.

Figure 6: UK coal plants: operating state and capacity utilization



Operating state refers to the percentage of coal plants being active (i.e. producing electricity 1/0). Capacity utilization gives the share of electricity produced relative to total available capacity for those coal plants that are active.

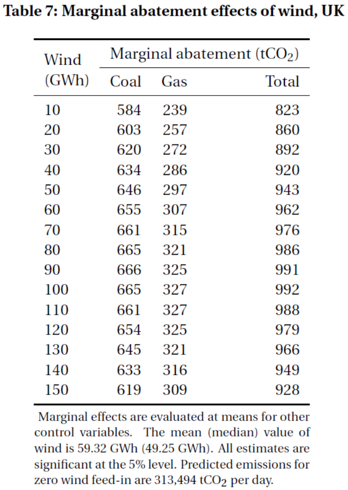


Table 7: Marginal abatement effects of wind, UK

Wind (GWh)	Marginal abatement (tCO_2)		
	Coal	Gas	Total
10	584	239	823
20	603	257	860
30	620	272	892
40	634	286	920
50	646	297	943
60	655	307	962
70	661	315	976
80	665	321	986
90	666	325	991
100	665	327	992
110	661	327	988
120	654	325	979
130	645	321	966
140	633	316	949
150	619	309	928

Marginal effects are evaluated at means for other control variables. The mean (median) value of wind is 59.32 GWh (49.25 GWh). All estimates are significant at the 5% level. Predicted emissions for zero wind feed-in are 313,494 tCO_2 per day.

- On average, wind in UK is more effective than in DE
- We evaluate effectiveness of wind conditional on mean carbon price of €20/tCO2, at which many coal and gas plants have already switched their positions, so that wind offsets a large fraction of *coal* emissions
- Mean wind (60 GWh) marginally replaces 962 tCO2 and **17%** of total daily emissions

Cost effectiveness of climate policies

We focus on **directly associable costs** of the various policies

- Carbon price times associable emissions offset
- Direct subsidies for wind and solar power (from CEER reports)

Limitations:

- We do not distinguish who pays the costs (producers or consumers)
- We do not account for potential negative externalities of these policies (e.g. pollution permits being freed up for use elsewhere in the EU ETS system; "water-bed effect")

DE: Cost effectiveness of climate policies

Carbon pricing

- Decreasing costs of marginal abatement within range of observed carbon prices (€4–€16)
- At sample mean of €8/tCO2, it costs €52 to replace one tCO2
- **At €16, it costs only €41 to abate an additional tonne of CO2**

Wind

- On average, 1 MWh of wind offsets 0.386 tCO2
- Subsidies per MWh feed-in of onshore and offshore wind are €64.71 and €159.07 in 2017
- Ratio of installed capacity of onshore to offshore wind is 84.4% to 15.6%
- **Average costs of wind = €204 per tCO2**
  $(= (€64.71 \cdot 0.844 + €159.07 \cdot 0.156)/0.386\ tCO_2)$

Solar

- On average, 1 MWh of solar offsets (only) 0.270 tCO_2, but receives high subsidies of €264.41 per MWh
- **Average costs of solar = €979/tCO2** $(=€264.41/0.270)$

UK: Cost effectiveness of climate policies

Carbon pricing

- At mean carbon price of €20/tCO2, costs of marginal abatement are €66 per additional tCO2
- **At (relatively high) carbon price of €35/tCO2, it costs only €30 to abate an additional tonne of CO2**
- For carbon prices beyond €36 the costs of marginal abatement increase again (→ little scope left for replacing further coal-based emissions)

Wind

- **Average costs of wind = €54/tCO2**
- This is because (i) UK's wind is more effective in abating emissions and (ii) subsidies for wind decreased substantially over time (to €52/MWh)
- UK's share of wind is much lower than in DE; for higher wind shares, we expect lower efficiency and thus higher costs

Conclusion

- We compare the (cost) effectiveness of first-best policy (emissions price), with widely applied second-best policies (subsidization of wind or solar) in DE and UK electricity markets
- DE's focus is on subsidizing RES; UK follows significant carbon pricing
- Main finding: a sufficiently high price on emissions is the most cost-effective policy to reduce emissions
    - DE: at a carbon price of €16, the marginal abatement costs are €41/tCO2. This policy would offset already 21% of total emissions.
    - Marginal abatement costs of wind are €204/tCO_2 and of solar are €979/tCO_2 (!)
    - Wind outperforms solar
    - Similar story for UK: (at €36/tCO2 it costs €30 to replace one tCO2; total emissions are reduced by 31%)
    - UK wind: wind is more effective for (yet) low feed-in and evaluated at high carbon price
- Policy implication: unilateral policies can work, but pre-existing structures are important

Appendix

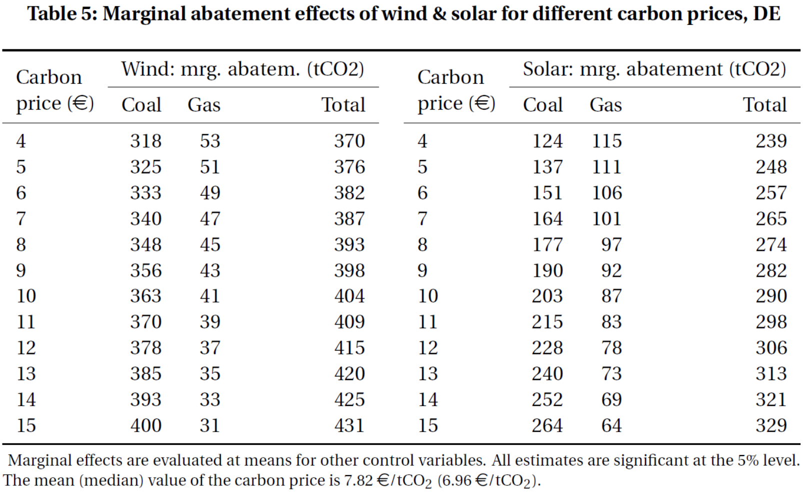


Table 5: Marginal abatement effects of wind & solar for different carbon prices, DE

Carbon price (€)	Wind: mrg. abatem. (tCO2)			Carbon price (€)	Solar: mrg. abatement (tCO2)		
	Coal	Gas	Total		Coal	Gas	Total
4	318	53	370	4	124	115	239
5	325	51	376	5	137	111	248
6	333	49	382	6	151	106	257
7	340	47	387	7	164	101	265
8	348	45	393	8	177	97	274
9	356	43	398	9	190	92	282
10	363	41	404	10	203	87	290
11	370	39	409	11	215	83	298
12	378	37	415	12	228	78	306
13	385	35	420	13	240	73	313
14	393	33	425	14	252	69	321
15	400	31	431	15	264	64	329

Marginal effects are evaluated at means for other control variables. All estimates are significant at the 5% level. The mean (median) value of the carbon price is 7.82 €/tCO_2 (6.96 €/tCO_2).

Appendix

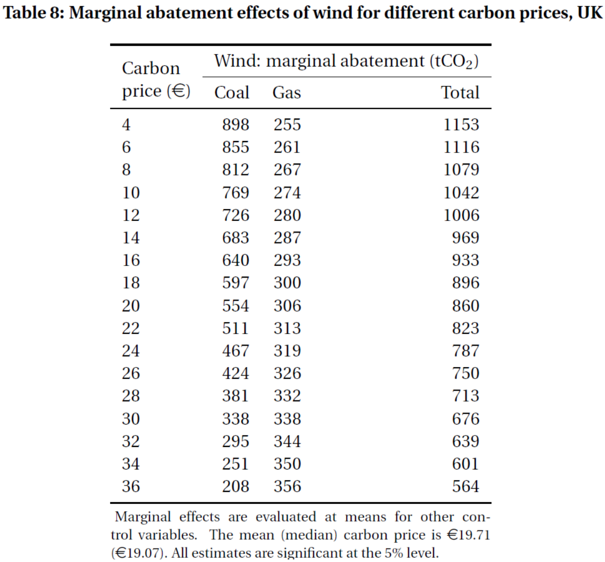


Table 8: Marginal abatement effects of wind for different carbon prices, UK

Carbon price (€)	Wind: marginal abatement (tCO_2)		
	Coal	Gas	Total
4	898	255	1153
6	855	261	1116
8	812	267	1079
10	769	274	1042
12	726	280	1006
14	683	287	969
16	640	293	933
18	597	300	896
20	554	306	860
22	511	313	823
24	467	319	787
26	424	326	750
28	381	332	713
30	338	338	676
32	295	344	639
34	251	350	601
36	208	356	564

Marginal effects are evaluated at means for other control variables. The mean (median) carbon price is €19.71 (€19.07). All estimates are significant at the 5% level.