

Modelling the UK's CO2 Emissions

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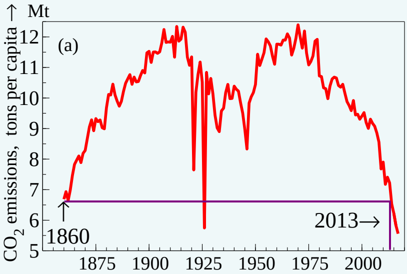
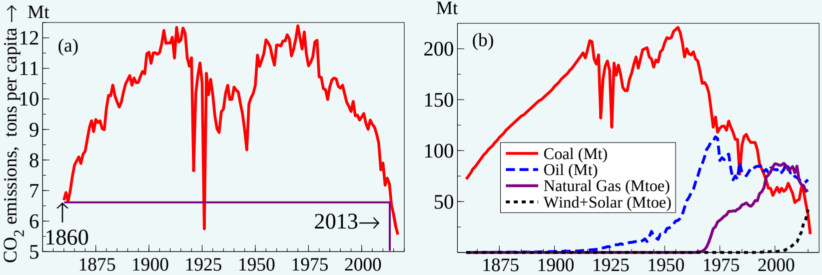
UK CO2 emissions and fossil fuels



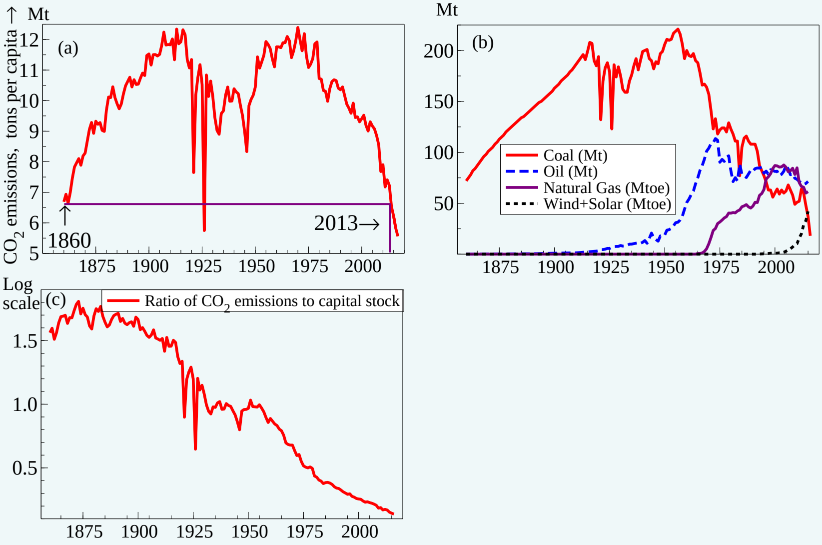
CO_2 emissions p.c. below 1860 level, yet real incomes >**7**-fold higher

UK CO2 emissions and fossil fuels



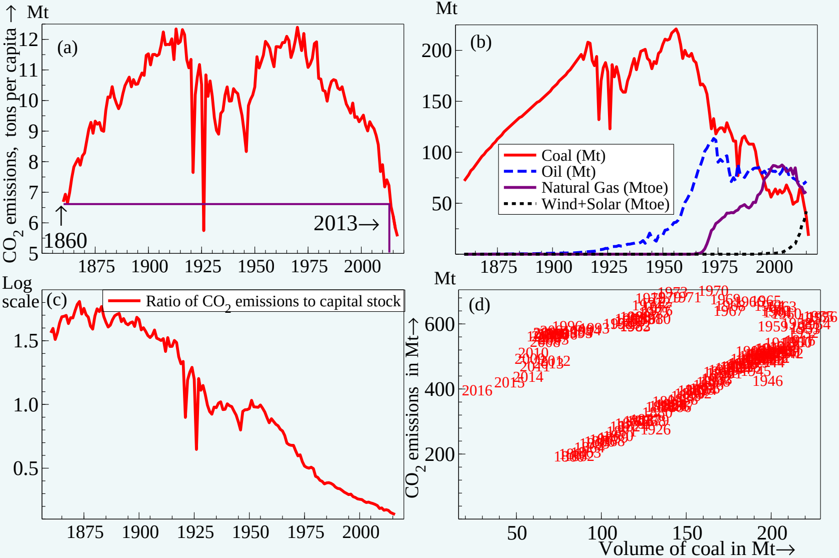
CO_2 emissions mainly driven by coal usage till mid-1970s; drop in oil use after crises

UK CO2 emissions and fossil fuels



CO_2 emissions have fallen by **92%** relative to capital stock

UK CO2 emissions and fossil fuels



CO_2 emissions have no constant relations to individual fuel usages, and all time series are highly non-stationary.

To capture changing relations, the model includes:

(a) the 2 main CO_2 emitters, coal and oil, + capital stock & GDP;
(b) dynamics for adjustments to changes in technology, legislation & fuel prices;
(c) impulse indicators for outliers (e.g., from strike action);
(d) step indicators for major permanent shifts (often policy induced).

Modelling changing relationships: UK CO2 emissions

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Both linear and log-linear relations were investigated, but linear models were strongly preferred.

Powerful new modelling tool called indicator saturation: impulse (IIS) and step (SIS).
Indicators (c) & (d) only capture features not explained by (a)–(b).

Mis-specification tests check the selected model is well specified.

Found 3 large step indicators, also identifiable with major events:

1925: Act of Parliament creating UK's nationwide electricity grid.

1969: start of conversion from coal gas to natural gas.

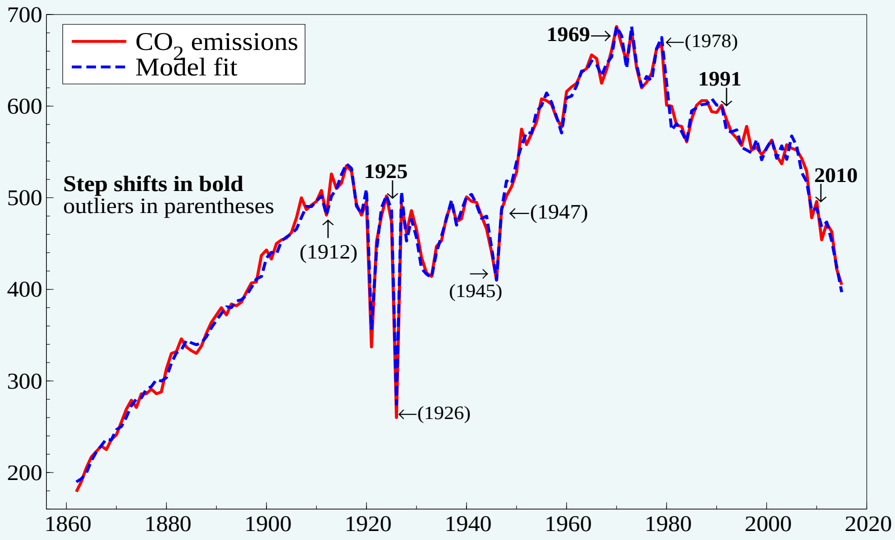
2010: follows implementation of the UK's Climate Change Act of 2008 and EU's renewables directive of 2009.

We did not impose that policy had an effect–the data tell us it did.

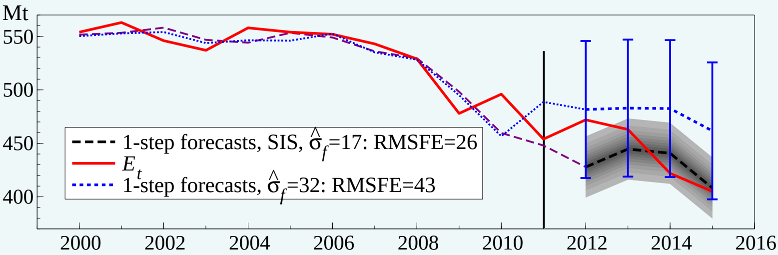
Also found 1991: emissions higher later than model explains.
Long-run equilibrium-correction (cointegrating) relation was:

$$\widetilde{\mathsf{E}}_t = \underset{(0.07)}{2.67}\ \mathbf{Coal}_t + \underset{(0.20)}{2.06}\ \mathbf{Oil}_t + \underset{(0.05)}{0.20}\ \mathbf{Capital}_t - \underset{(2.25)}{8.23}\ \mathbf{GDP}_t + \underset{(6.7)}{41.5}\ S_{1925} - \underset{(16.5)}{72.4}\ S_{1969} - \underset{(14.0)}{43.4}\ S_{1991} \quad (1)$$

All variables significant at 1% (S_{1991} was marginal at 2.3%).
Being at the end of the estimation sample, S_{2010} was left unrestricted.

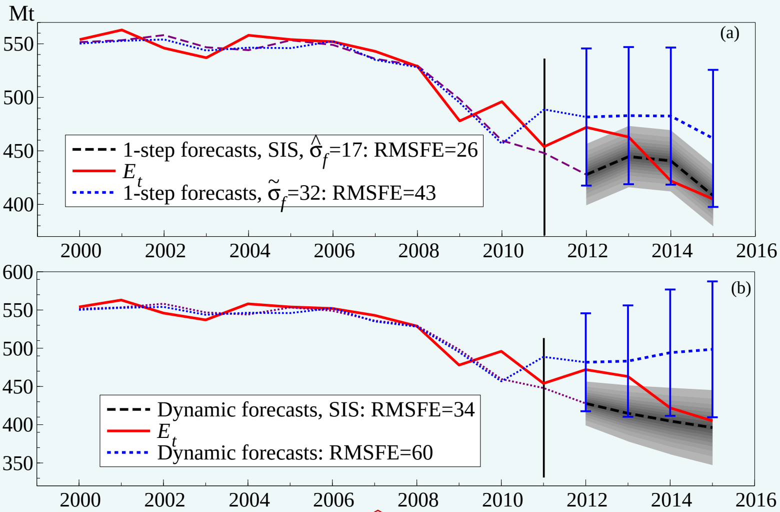


Actual and fitted values for total UK CO_2 emissions.



(a) Outcomes and 1-step forecasts $\pm 2\widehat{\sigma}_f$ as bars and fans without and with indicators.

System 1-step and dynamic forecasts

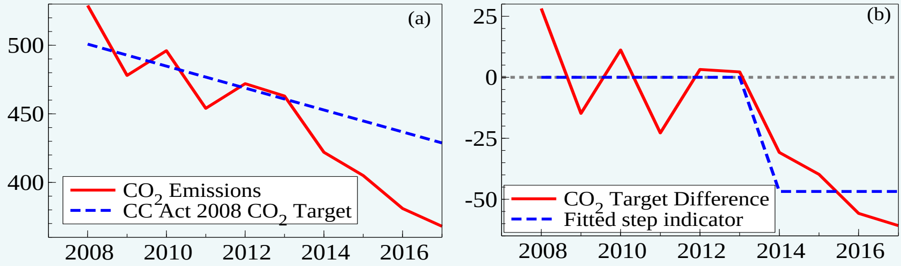


(a) Outcomes and 1-step forecasts $\pm 2\widehat{\sigma}_f$ as bars and fans without and with indicators;

(b) **Outcomes and h-step forecasts $\pm 2\widehat{\sigma}_f$ as bars and fans without and with indicators.**

Testing the UK's achievement of its 2008 Climate Change Act targets

5-year targets converted to annual magnitudes, starting 20Mt above and ending 20Mt below average, scaled by 0.8 as share of CO_2 in all UK greenhouse gases.



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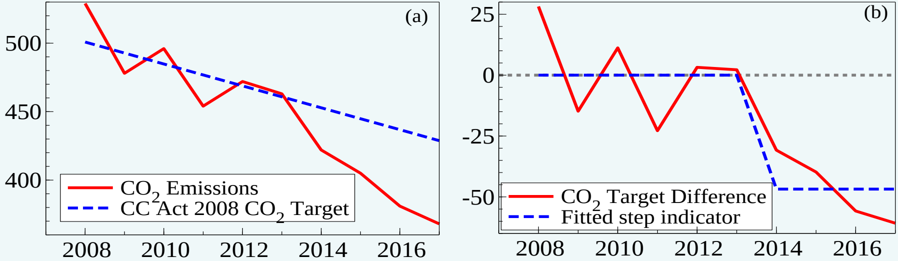

(a) Tested difference between targets and outcomes being zero from 2009: null of "emissions=targets" strongly rejected with a negative mean of -18Mt pa, & t-test of -2.67 ($p < 0.03$): panel (a).

(b) SIS found step of -46.8 in 2013 with $t = -5.9$: panel (b).

Similar approach could evaluate if countries meet their Paris Accord NDCs.

Simulating UK's aim of 80% reduction by 2050

CO_2 emissions to drop to 120 Mt pa. from 1990 base of 590 Mt.

Simulated a scenario with no coal and 70% fall in oil use to around 20 Mt p.a., implicitly with a 75% reduction in CO_2 emissions from natural gas & 50% from agriculture, construction and waste (currently c 100 Mt p.a.).

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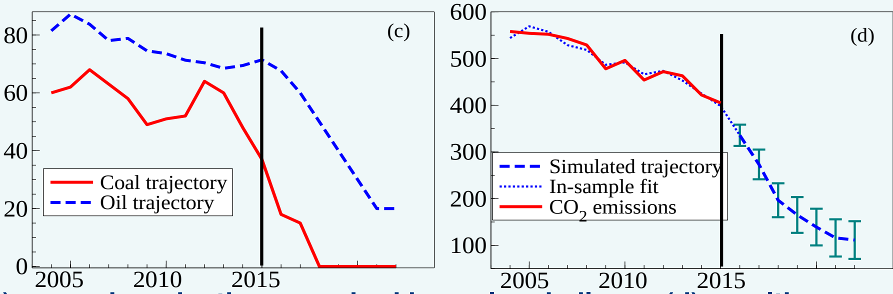

(c) scenario reductions required in coal and oil use; (d) resulting reductions in CO_2 emissions from model, compressed to 5-year intervals after 2015.

Need to add back CO_2 embedded in net imports for full appraisal.

Conclusions on policy implications

UK climate policy has been effective:

large reductions in CO_2 emissions have had only a small aggregate cost,
but local losses have not been properly addressed;

'stranded assets' could be a potential problem if legislation imposes lower CO_2 emissions targets.

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Thank you

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Following this path, we **first** find for $T = 1862–2011$, testing constancy over 2012–2015:

$$
\begin{aligned}
E_t = &\underset{(0.07)}{0.51} E_{t-1} + \underset{(0.11)}{2.44} C_t - \underset{(0.19)}{1.14} C_{t-1} + \underset{(0.26)}{1.03} K_t - \underset{(0.25)}{0.92} K_{t-1} \\
&+ \underset{(0.3)}{1.67} O_t - \underset{(0.35)}{0.689} O_{t-1} + \underset{(2.1)}{2.24} G_t - \underset{(2.1)}{6.34} G_{t-1} \\
&+ \underset{(12)}{54.6} 1_{1947} + \underset{(12)}{85.9} S_{1925} - \underset{(20)}{119} S_{1926} + \underset{(13)}{52.8} S_{1927} \\
&+ \underset{(11)}{51.9} S_{1945} - \underset{(11)}{49.6} S_{1946} - \underset{(8.6)}{34.0} S_{1969} - \underset{(13)}{36.3} S_{1983} \\
&+ \underset{(13)}{45.3} S_{1984} - \underset{(6.6)}{19.2} S_{1991} + \underset{(11)}{46.9} S_{2010} - \underset{(22)}{37.3}
\end{aligned}
\tag{2}
$$

$$\widehat{\sigma} = 10.1 \;\; R^2 = 0.994 \;\; F_{ARCH}(1, 148) = 3.87$$

$$F_{AR}(2, 127) = 2.13 \;\; F_{RESET}(2, 127) = 3.86^{*} \;\; F_{nl}(6, 141) = 8.72^{**}$$

$$\chi^2_{nd}(2) = 8.73^{*} \;\; F_{Het}(3, 120) = 0.87 \;\; F_{Chow}(4, 129) = 0.68$$

One impulse and **ten** step indicators selected despite $\alpha_1 = 0.001$.

Residual non-Normality suggests using a less tight criterion for IIS.

Stage 1: selecting indicators in the general model

Similar analysis applies to using both IIS and SIS: $\mathrm{N} > \mathrm{T}$ is no barrier for a multi-path algorithm that selects in large feasible blocks.

Using both IIS and SIS, we found **one** impulse (1947) and **10** step indicators, many of which can be combined as differences.

Stage 1: selecting indicators in the general model

Similar analysis applies to using both IIS and SIS: $N > T$ is no barrier for a multi-path algorithm that selects in large feasible blocks.

Using both IIS and SIS, we found **one** impulse (1947) and **10** step indicators, many of which can be combined as differences.

Step Date	Value	99% Lower	99% Upper	99% Range (±)	Coverage
1925	86	1925	1925	0	1.000
1926	−119	1926	1926	0	1.000
1927	54	1927	1927	0	0.991
1945	**52**	1944	1946	1	1.000
1946	−**50**	1945	1947	1	1.000
1969	−34	1967	1971	2	0.998
1983	−**36**	1982	1984	1	0.993
1984	**45**	1983	1985	1	0.999
1991	−19	1986	1996	5	0.991
2010	47	2009	2011	1	0.999

Confidence intervals for the selected break dates (see Hendry and Pretis, 2016).

Fourth, transforming to a model in differences and the lagged cointegration relation from (1), then re-estimating, revealed a significant non-normality test, so IIS was re-applied at 0.1%, which yielded (for 1861–2011, testing constancy over 2012–2015):

$$
\begin{aligned}
\Delta E_t = & \underset{(0.23)}{1.65}\ \Delta O_t + \underset{(0.09)}{2.45}\ \Delta C_t + \underset{(0.12)}{0.93}\ \Delta K_t - \underset{(0.06)}{0.43}\ Q_{t-1} - \underset{(9.9)}{60.2} \\
& + \underset{(9.5)}{41.7}\ S_{2010} + \underset{(8.7)}{71.1}\ \Delta^2 S_{1925} - \underset{(11)}{41.6}\ \Delta S_{1983} + \underset{(9.6)}{51.5}\ \Delta S_{1945} \\
& + \underset{(10)}{56.5}\ 1_{1947} - \underset{(9.5)}{30.9}\ 1_{1912} + \underset{(9.6)}{34.0}\ 1_{1970} + \underset{(9.6)}{30.7}\ 1_{1978} \qquad (3)
\end{aligned}
$$

$$
\widehat{\sigma} = 9.44 \;\; R^2 = 0.94 \;\; F_{ARCH}(1,149) = 1.77
$$
$$
F_{AR}(2,136) = 0.56 \;\; F_{RESET}(2,136) = 6.20^{**} \;\; F_{nl}(6,126) = 2.14^{*}
$$
$$
\chi^2_{nd}(2) = 3.76 \;\; F_{Het}(3,133) = 1.18 \;\; F_{Chow}(4,138) = 1.11
$$

Changes in oil, coal and the capital stock all lead to changes in emissions, which then equilibrates back to the long-run relation in (1). Q^2_{t-1} was marginally significant if added, and markedly reduced the significance of the RESET test.

Data definitions

E_t	=	CO_2 emissions, millions of tonnes (Mt)	[1], [2].
O_t	=	Net oil usage, millions of tonnes	[3]: 1 tonne = 0.984 imperial tons.
C_t	=	Coal volumes in millions of tonnes	[4].
G_t	=	real GDP, \$10 billions, 1985 prices	[5], [7], [8]a (1993), [10].
K_t	=	capital stock, \$billions, 1985 prices	[6], [7], [8]c (1972,1979,1988,1992)
1_{abcd}	=	impulse indicator of unity in year $abcd$	
S_{abcd}	=	step indicator of unity up to year $abcd$	
Δx_t	=	$(x_t - x_{t-1})$ for any variable x_t	
$\Delta^2 x_t$	=	$\Delta x_t - \Delta x_{t-1}$	

Sources:

[1] World Resources Institute http://www.wri.org/our-work/project/cait-climate-data-explorer and https://www.gov.uk/government/collections/final-uk-greenhouse-gas-emissions-national-statistics;
[2] Office for National Statistics (ONS) https://www.gov.uk/government/statistics/provisional-uk-greenhouse-gas-emissions-national-statistics-2015;
[3] Crude oil and petroleum products: production, imports and exports 1890 to 2015 Department for Business, Energy and Industrial Strategy (Beis);
[4] Beis and Carbon Brief http://www.carbonbrief.org/analysis-uk-cuts-carbon-record-coal-drop;
[5] ONS https://www.ons.gov.uk/economy/nationalaccounts/uksectoraccounts#timeseries;
[6] ONS https://www.ons.gov.uk/economy/nationalaccounts/uksectoraccounts/bulletins/capitalstocksconsumptionoffixedcapital/2014-11-14#capital
[7] Mitchell (1988) and Feinstein (1972);
[8] Charles Bean (from (a) *Economic Trends Annual Supplements*, (b) *Annual Abstract of Statistics*, (c) *Department of Employment Gazette*, and (d) *National Income and Expenditure*);
[9] UN Statistical Yearbook and Christopher Gilbert;

[10] ONS, *Blue Book* and *Annual Abstract of Statistics* and *Economic Trends Annual Supplement*.

Relative emissions of fuel sources

Coal (anthracite)	228.6
Coal (bituminous)	205.7
Coal (lignite)	215.4
Coal (sub-bituminous)	214.3
Diesel fuel & heating oil	161.3
Gasoline	157.2
Propane	139.0
Natural gas	117.0

Table 3: Pounds of CO_2 emitted per million British thermal units (Btu) of energy produced.
Source: US Department of Energy
https://www.eia.gov/tools/faqs/faq.php?id=73&t=11.

Estimated UK electricity costs for projects starting in 2015

Power generating technology| costs £/MWh	Low	Central	High
Nuclear PWR (Pressurized Water Reactor)(a)	82	93	121
Solar Large-scale PV (Photovoltaic)	71	80	94
Wind Onshore	**47**	**62**	76
Wind Offshore	90	102	115
Biomass	85	87	88
Natural Gas Combined Cycle Gas Turbine	65	66	**68**
CCGT with CCS	102	110	123
Open-Cycle **Gas** Turbine	157	162	170
Advanced Supercritical **Coal** Oxy-comb. CCS	124	134	153
Coal IGCC with CCS (b)	137	148	171

(a) New nuclear power: guaranteed strike price of £92.50/MWh for Hinkley Point C in 2023

(b) IGCC =Integrated Gasification Combined Cycle