Imperial College London

Taxes, Subsidies or Regulation: Why have Britain's CO_2 emissions from electricity halved?

Richard Green, Imperial College Business School
Iain Staffell, Centre for Environmental Policy

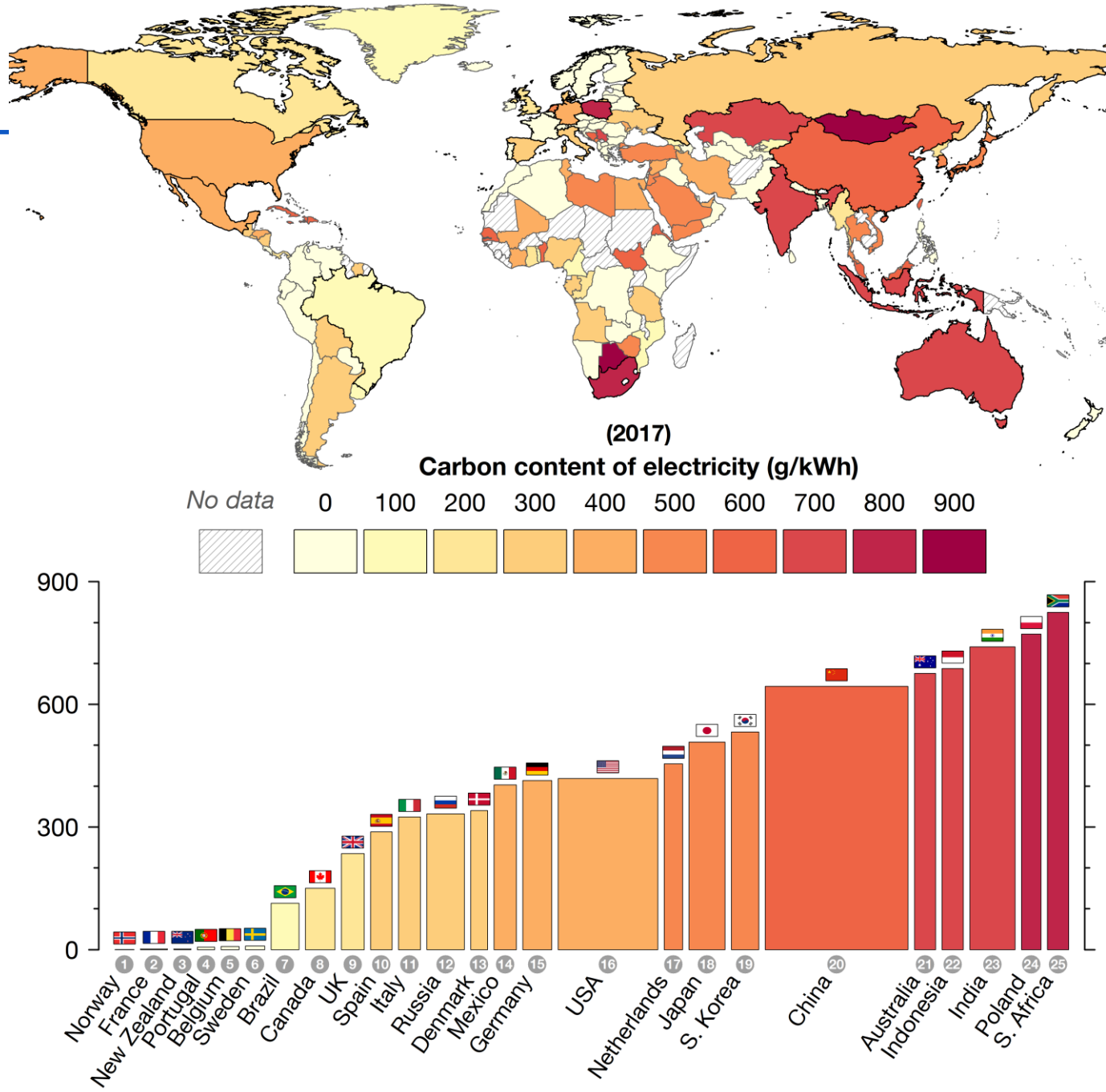
cep

Imperial College Business School

ETH Zürich, 15 October 2019

Clean power?

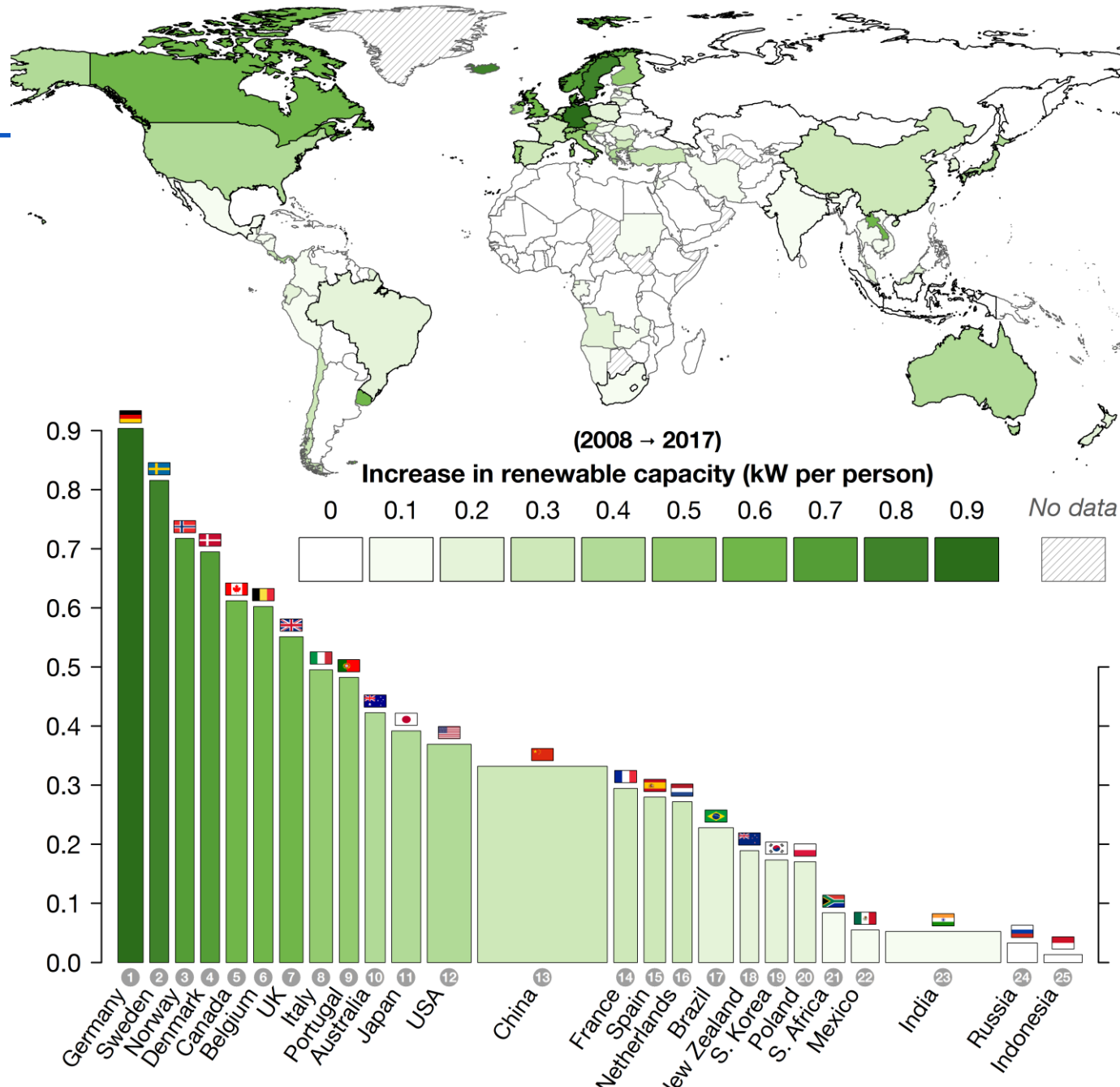
- Clean electricity is fundamental, able to drive decarbonisation of vehicles, heat and industry
- The 2017 global average carbon intensity of electricity was 440 gCO_2 per kWh consumed
- If China could reduce carbon intensity by a third to match USA, global CO_2 emissions would fall by 4%
- If China and USA could match the UK, global emissions would fall 9%



Source — Energy Revolution: A Global Outlook

Clean power?

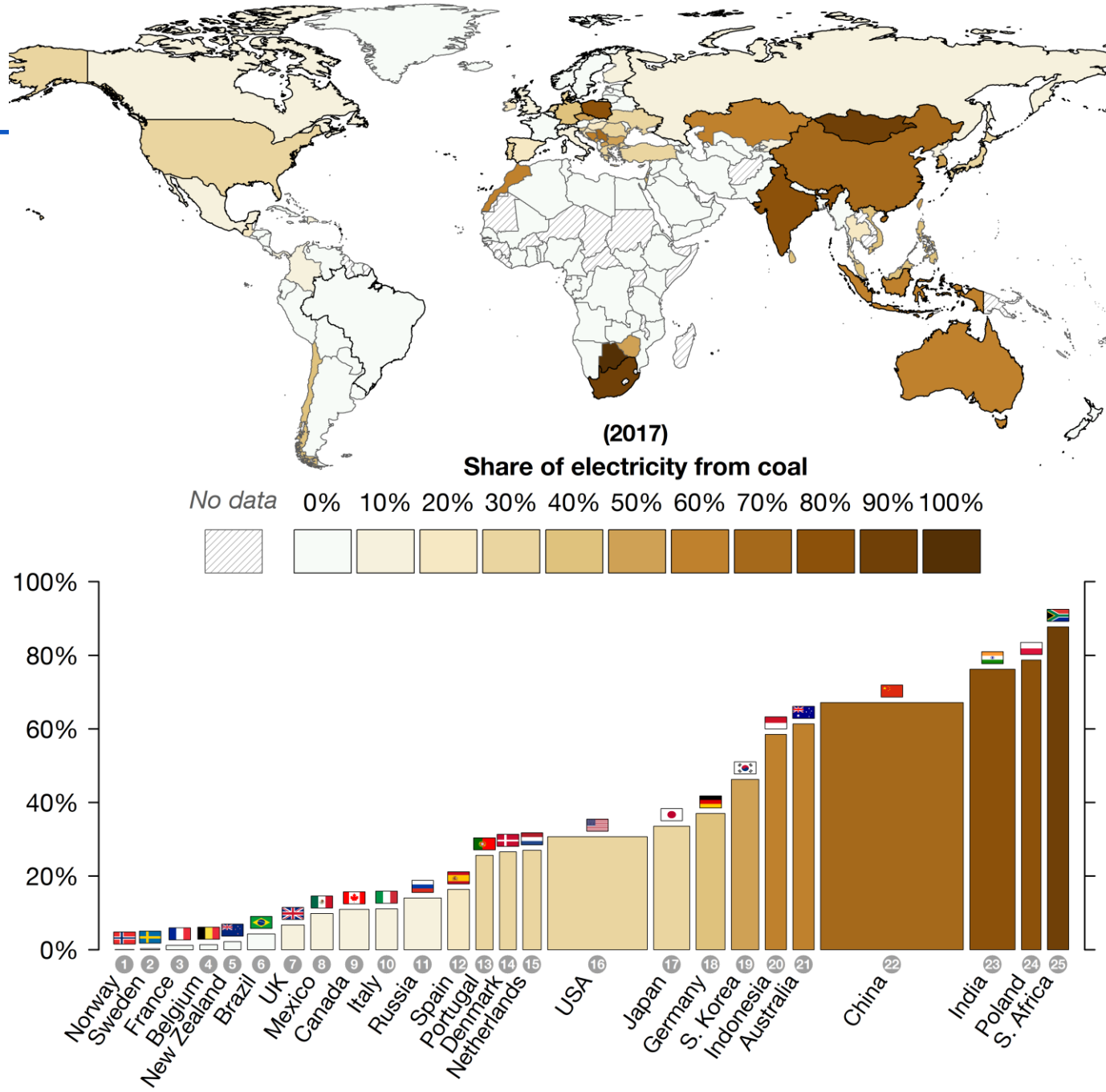
- Renewables formed more than half of all new generating capacity for the last three years running
- More than 1,100 GW installed globally over the last decade = 160 watts per capita
- Growth rates over the last decade:
  - 40% per annum for solar
  - 20% per annum for wind
  - 8% per annum for biomass & waste
  - 4% per annum for hydro



Source — Energy Revolution: A Global Outlook

Clean power?

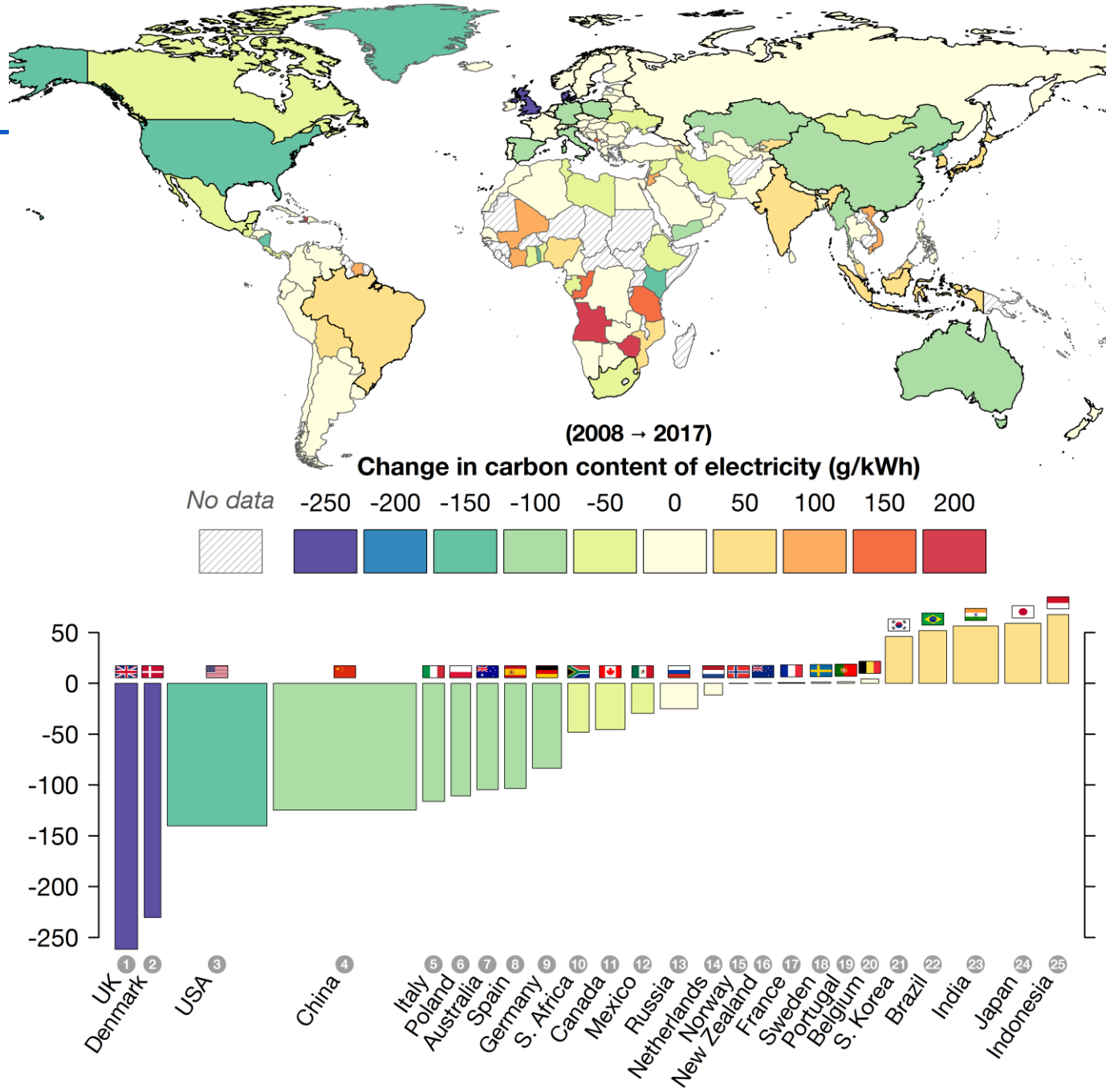
- Coal is the most polluting fuel, that has provided around 40% of the world's electricity for the last 30 years
- Particularly heavy reliance on coal across Asia
- Many barriers to powering past coal:
  - Strong industry lobbying
  - Job losses in mining
  - Security of energy supply
  - Maintaining low electricity bills



Source — Energy Revolution: A Global Outlook

Clean power?

- Global carbon intensity of electricity has fallen by only 5% over the last decade
- China and the US made big reductions, despite 'building a new coal power station every week', and trying to 'bring back coal'
- UK has seen the fastest power sector transformation over the last decade



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Clean power?

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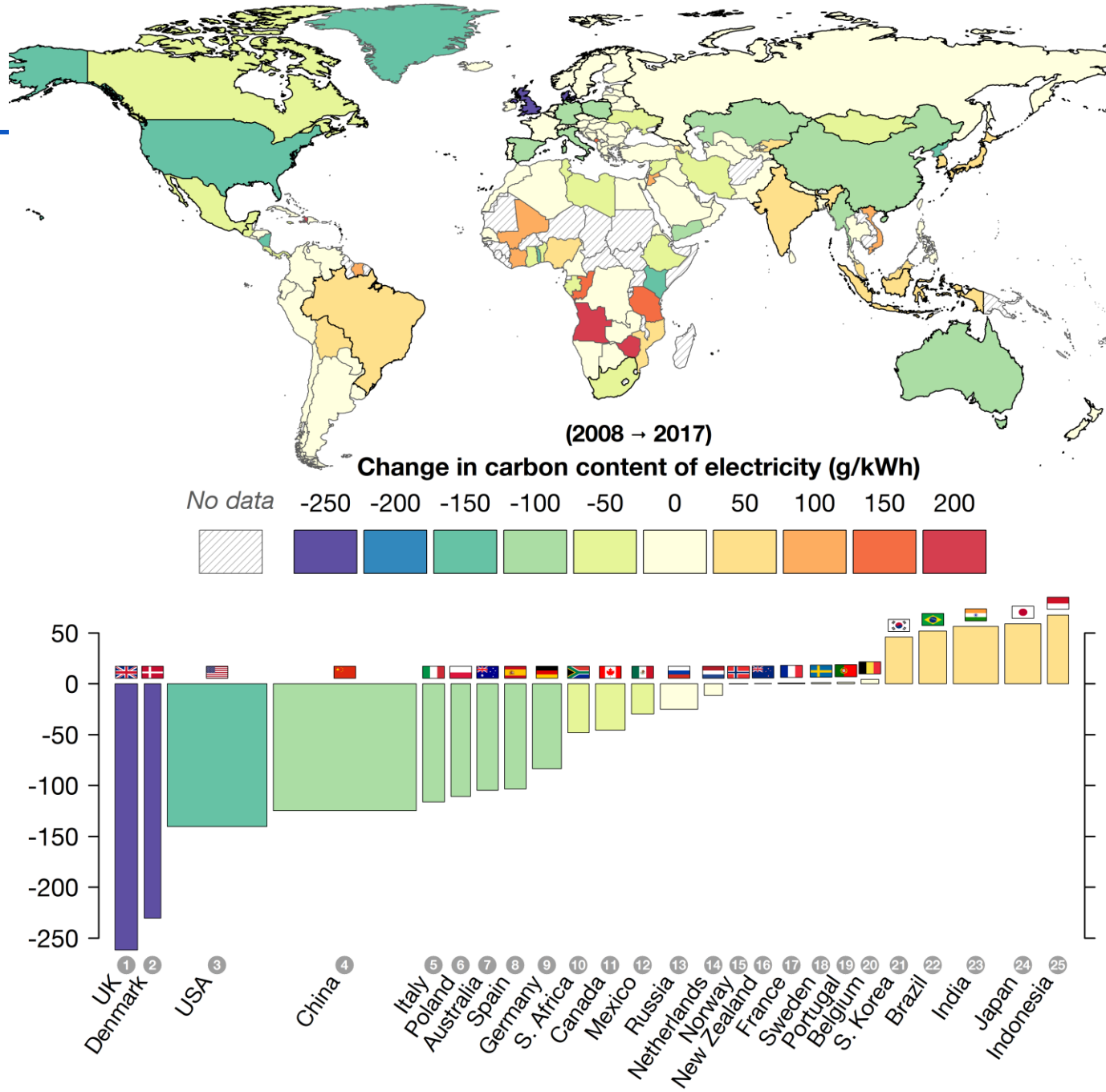
- UK has seen the fastest power sector transformation over the last decade
- Why?



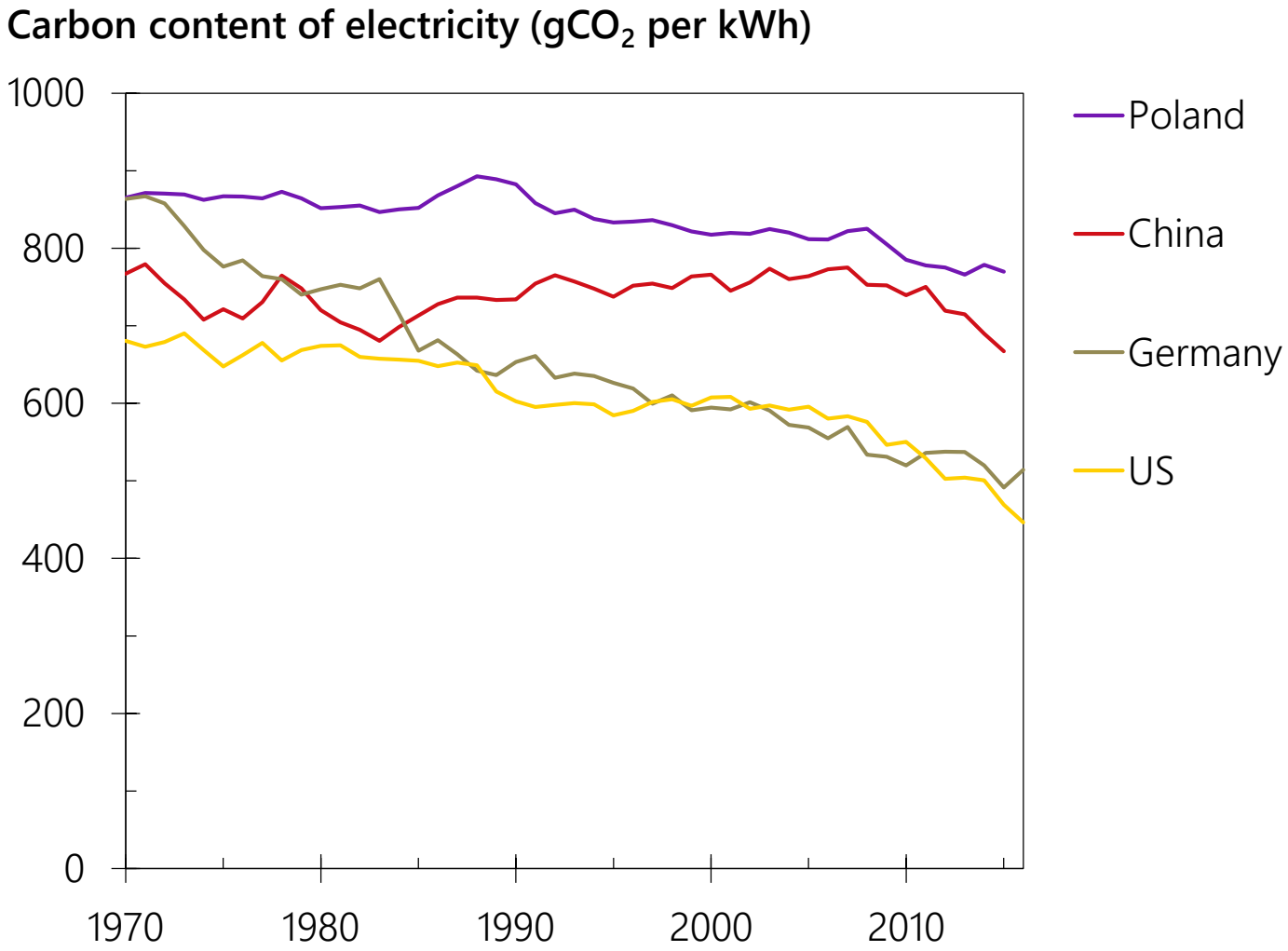
Source — Energy Revolution: A Global Outlook

Agenda

- How Britain's power system has changed
- Past studies of emissions savings
- Our approach
  - Shapley Value to assign reductions to changes
  - Simulation modelling – the enhanced merit order stack
- Results
  - What caused the fall in emissions
  - What did this do to prices?
  - What was cost-effective?

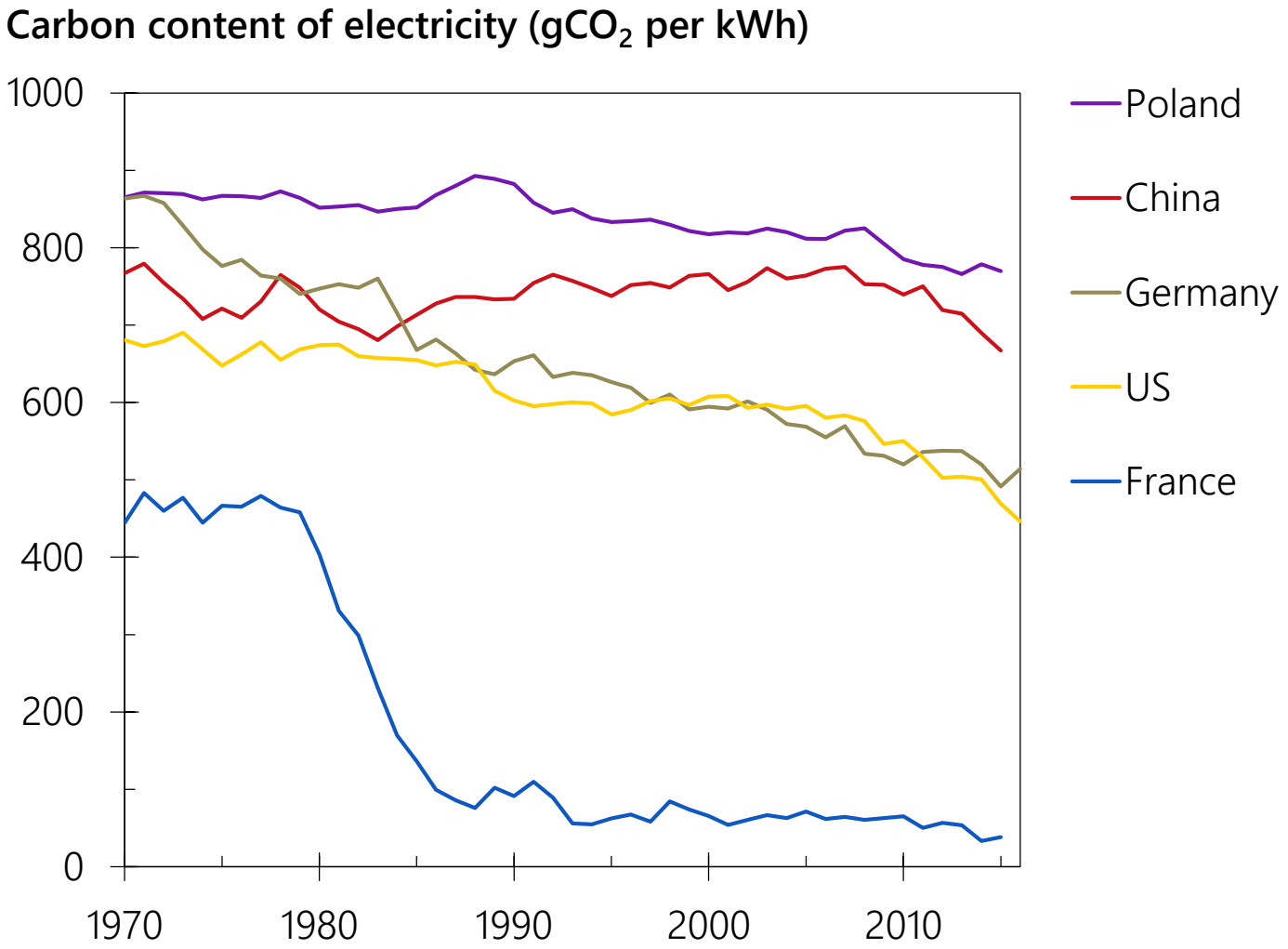
Power sector emissions

Power sector emissions



Source — Wilson, 2018, Nature Energy

Power sector emissions



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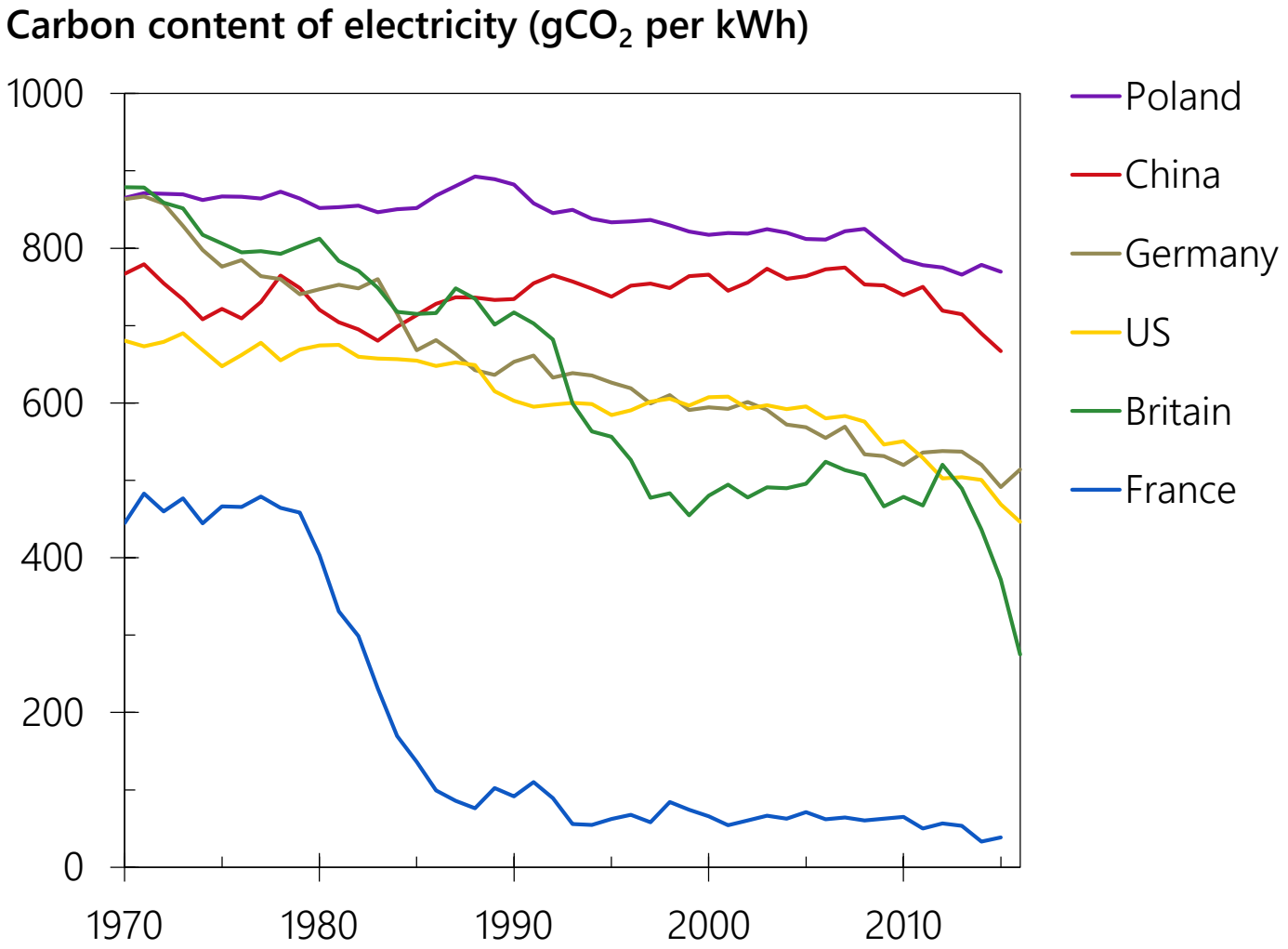
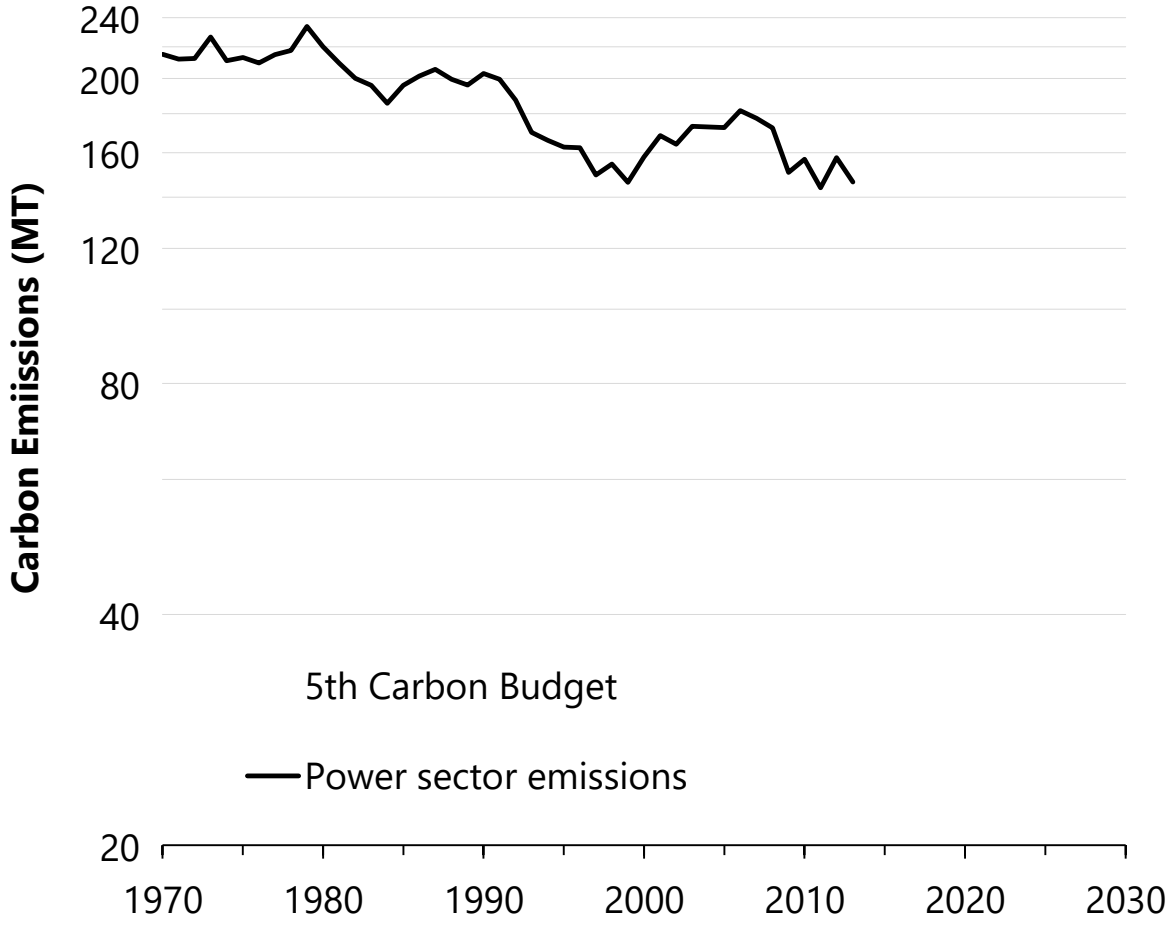
Power sector emissions



Source — Wilson, 2018, Nature Energy

Power sector emissions

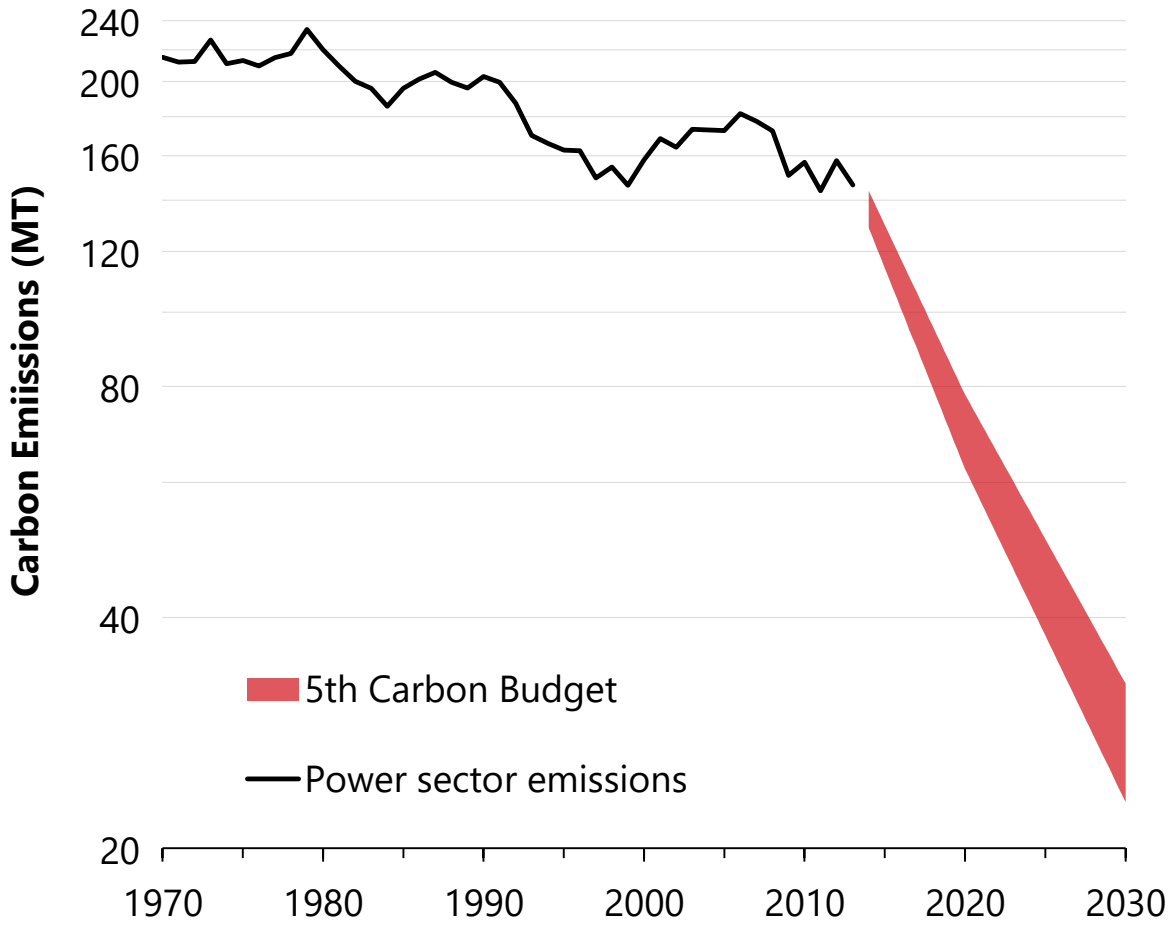
- The UK's power sector slowly decarbonised for 40 years



Source — Staffell, 2017, Energy Policy

Power sector emissions

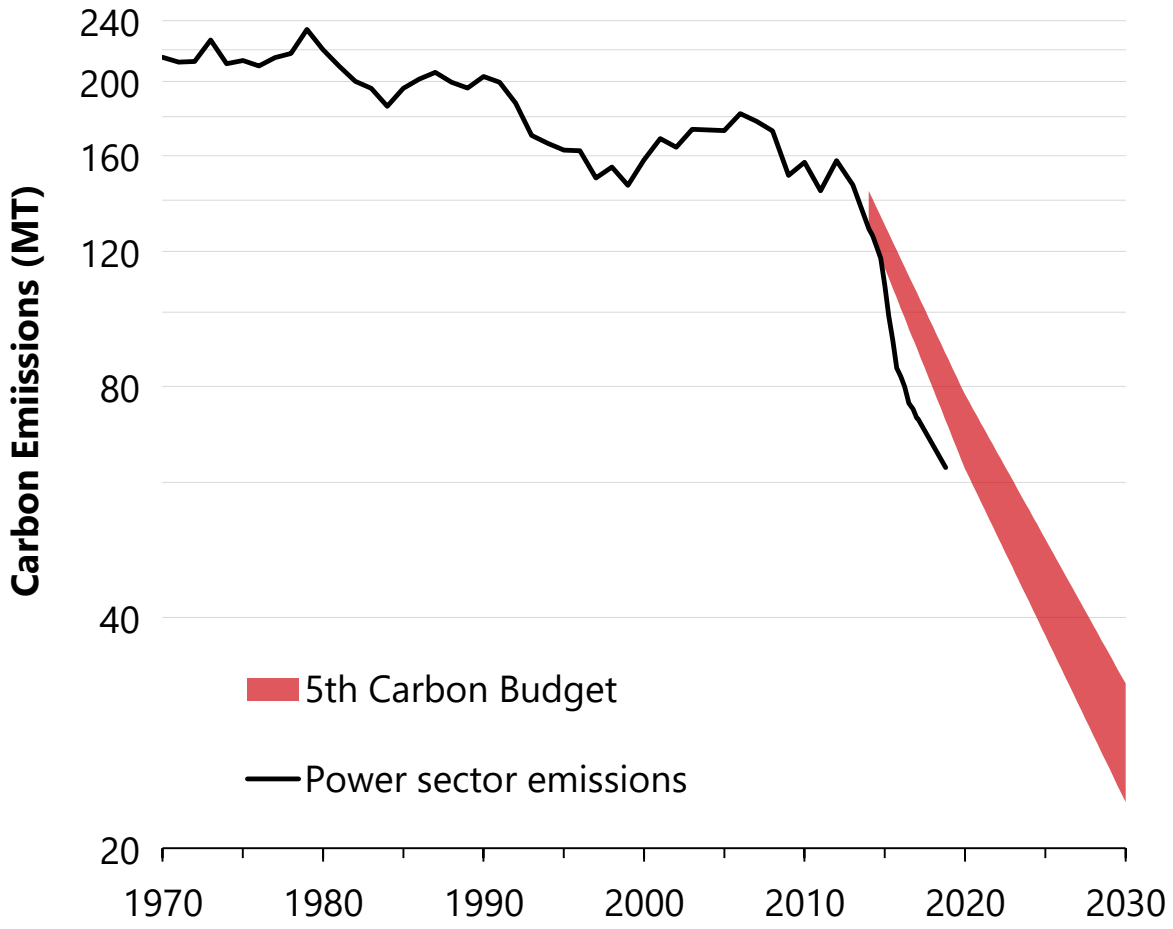
- The UK's power sector slowly decarbonised for 40 years
- But the law required 5x faster



Source — Staffell, 2017, Energy Policy

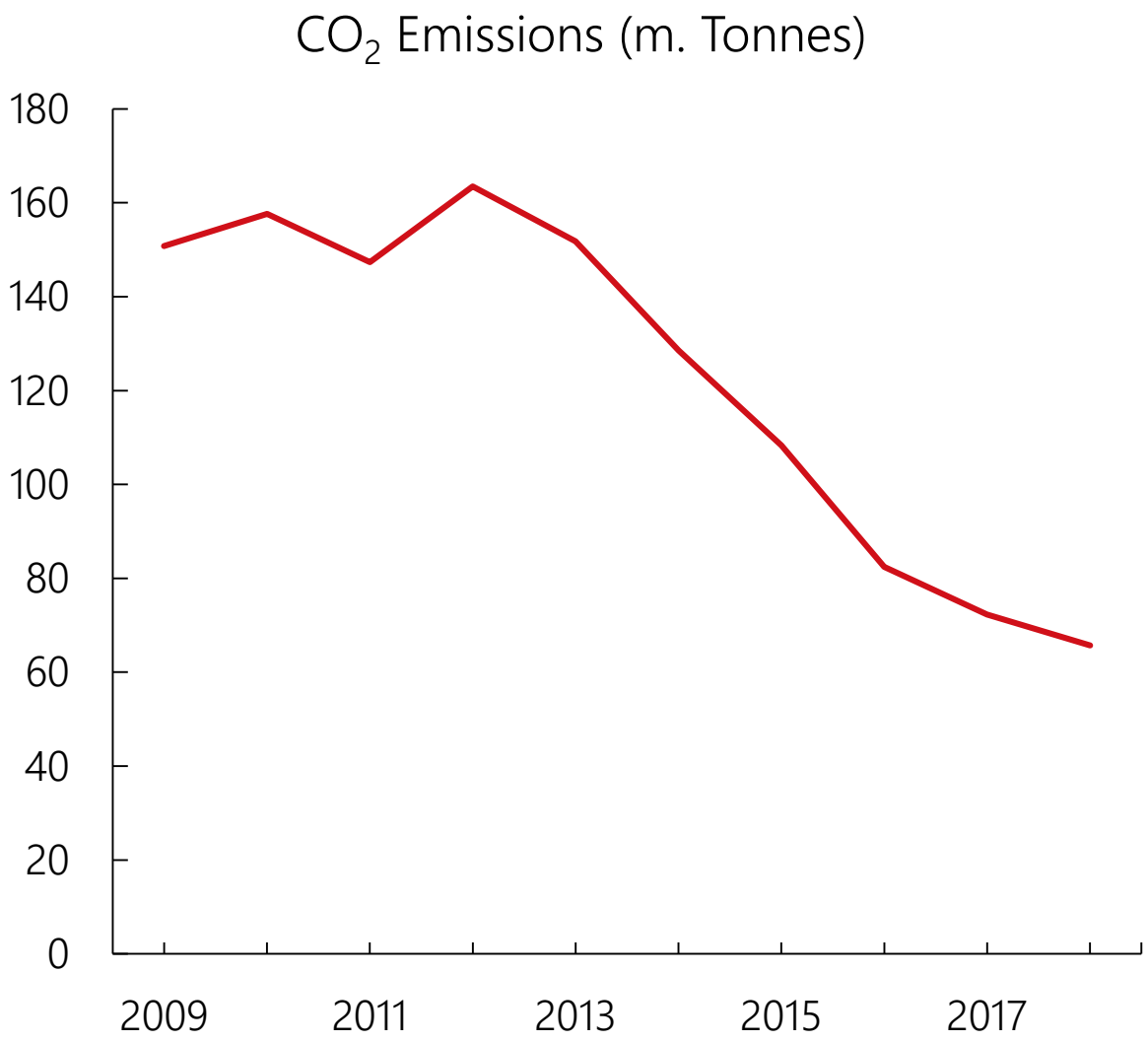
Power sector emissions

- The UK's power sector slowly decarbonised for 40 years
- But the law required 5x faster
- And somehow… it is working…



Source — Staffell, 2017, Energy Policy

What has changed?



Source — Electric Insights

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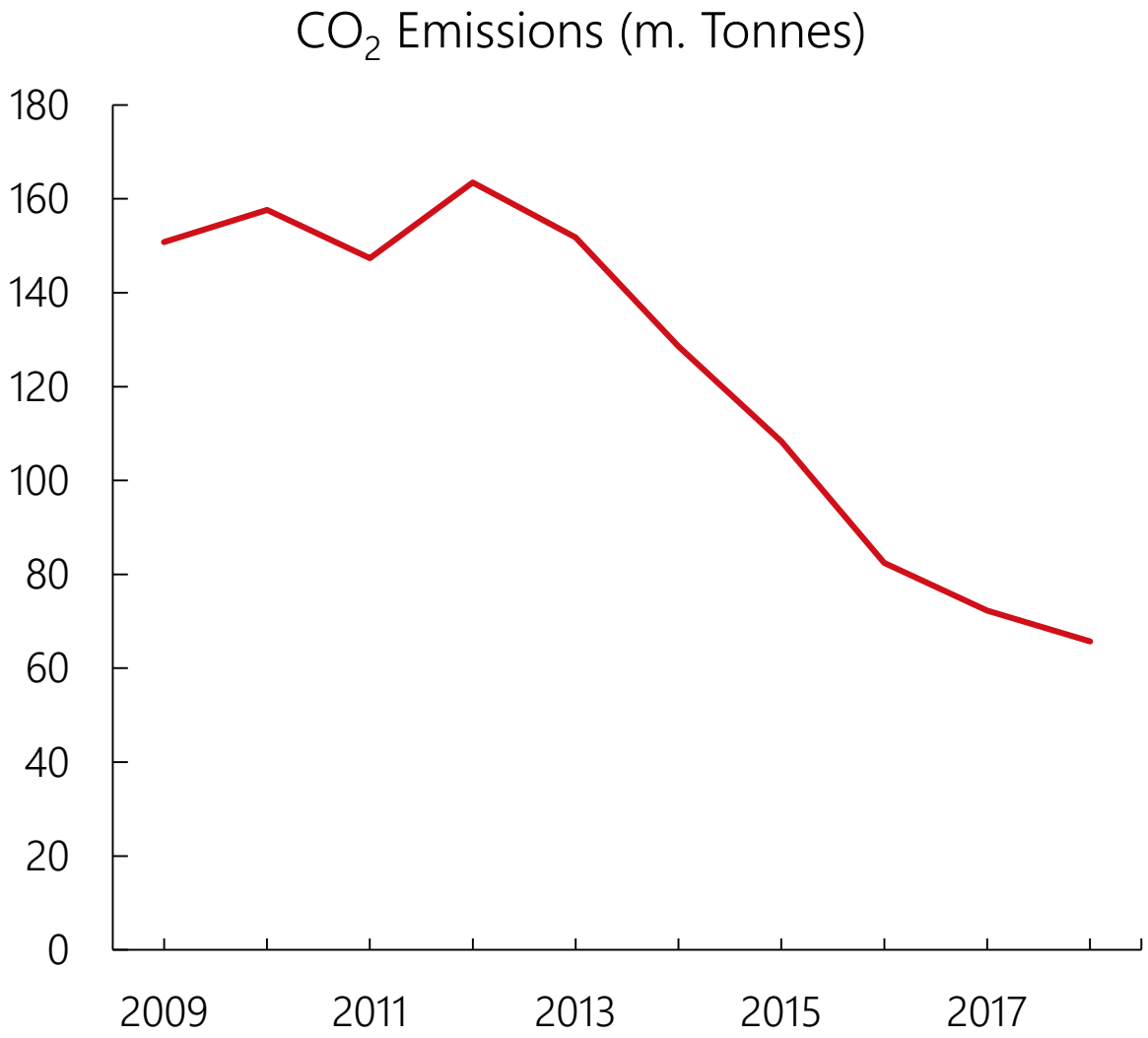

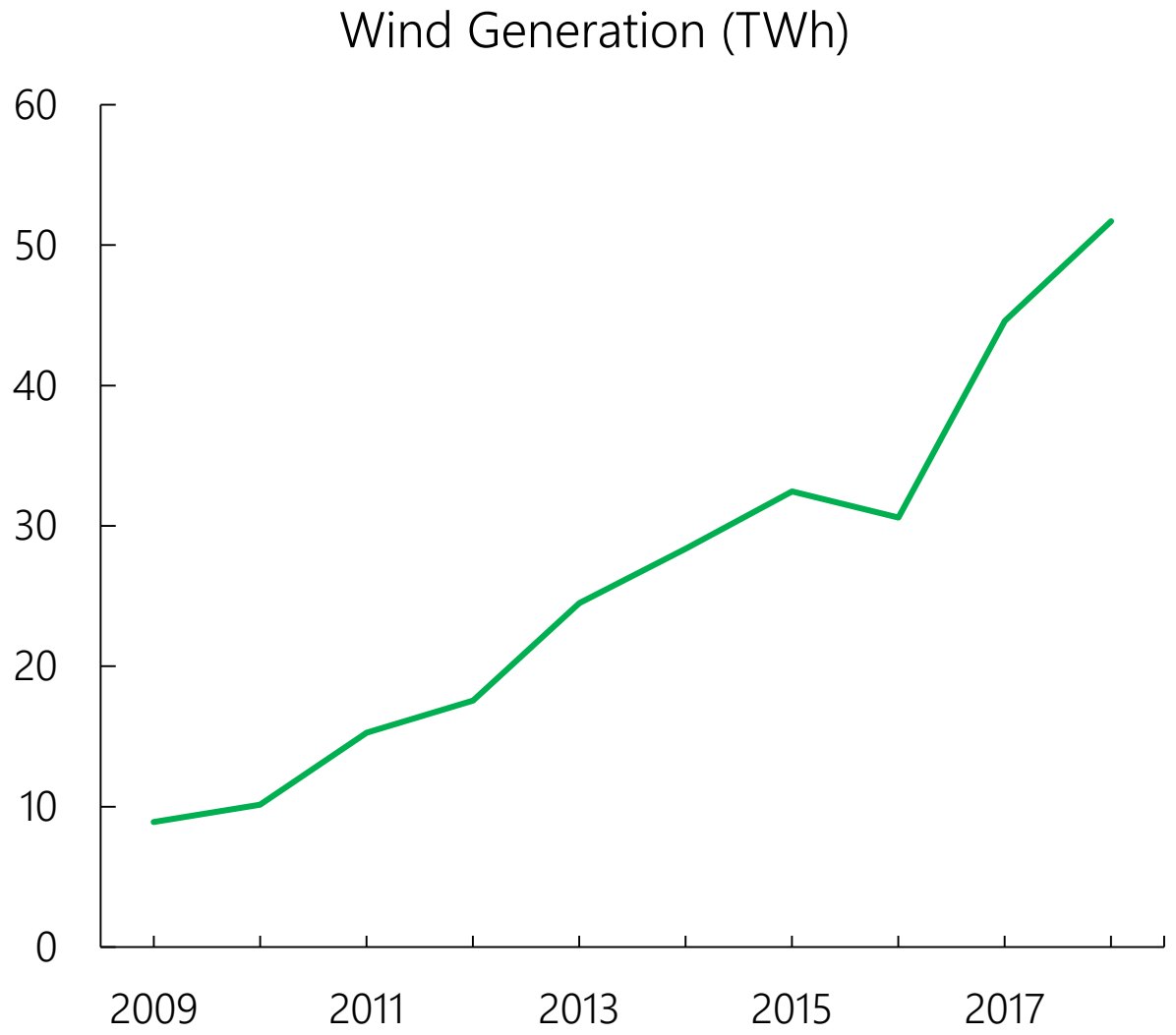

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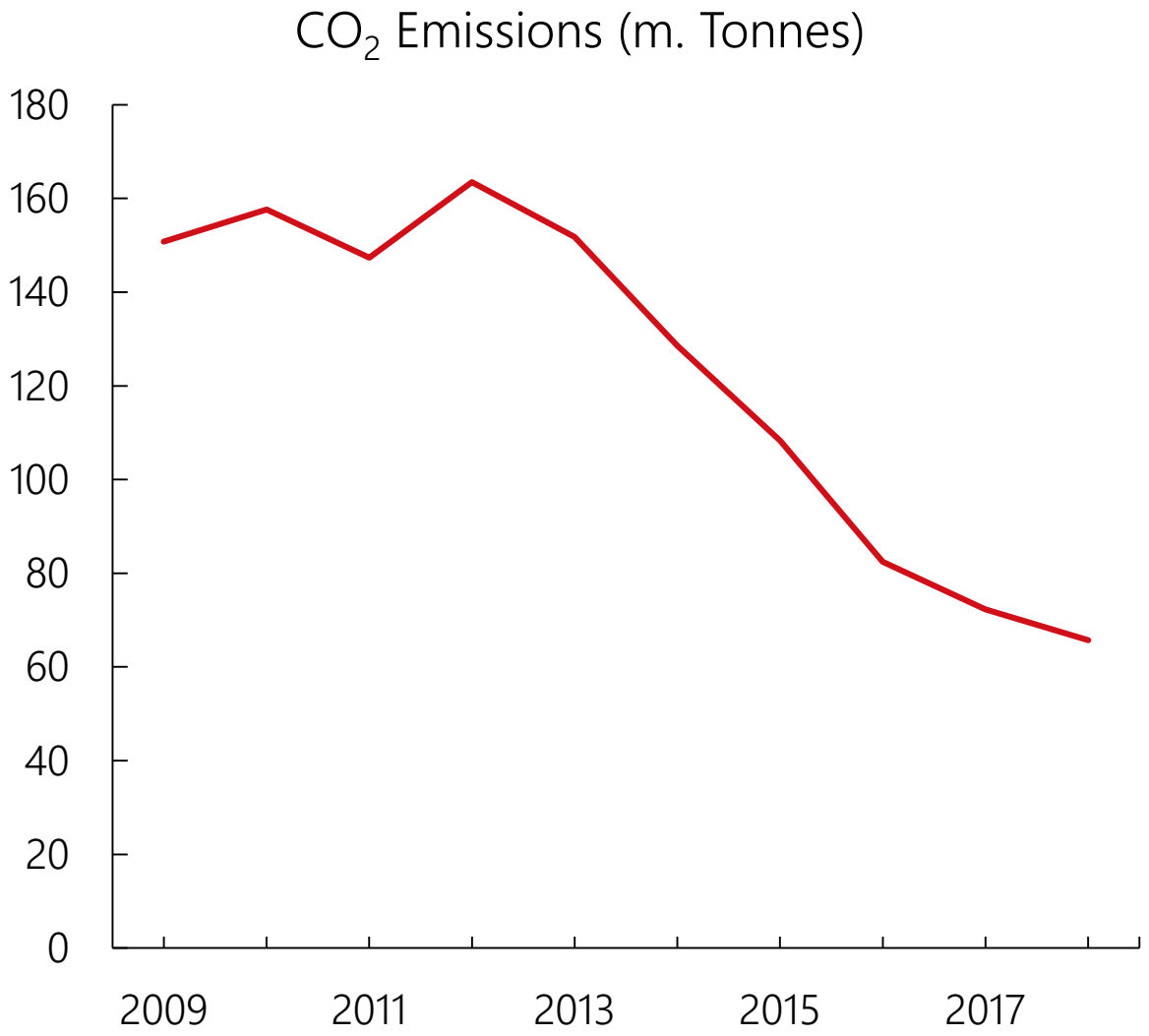

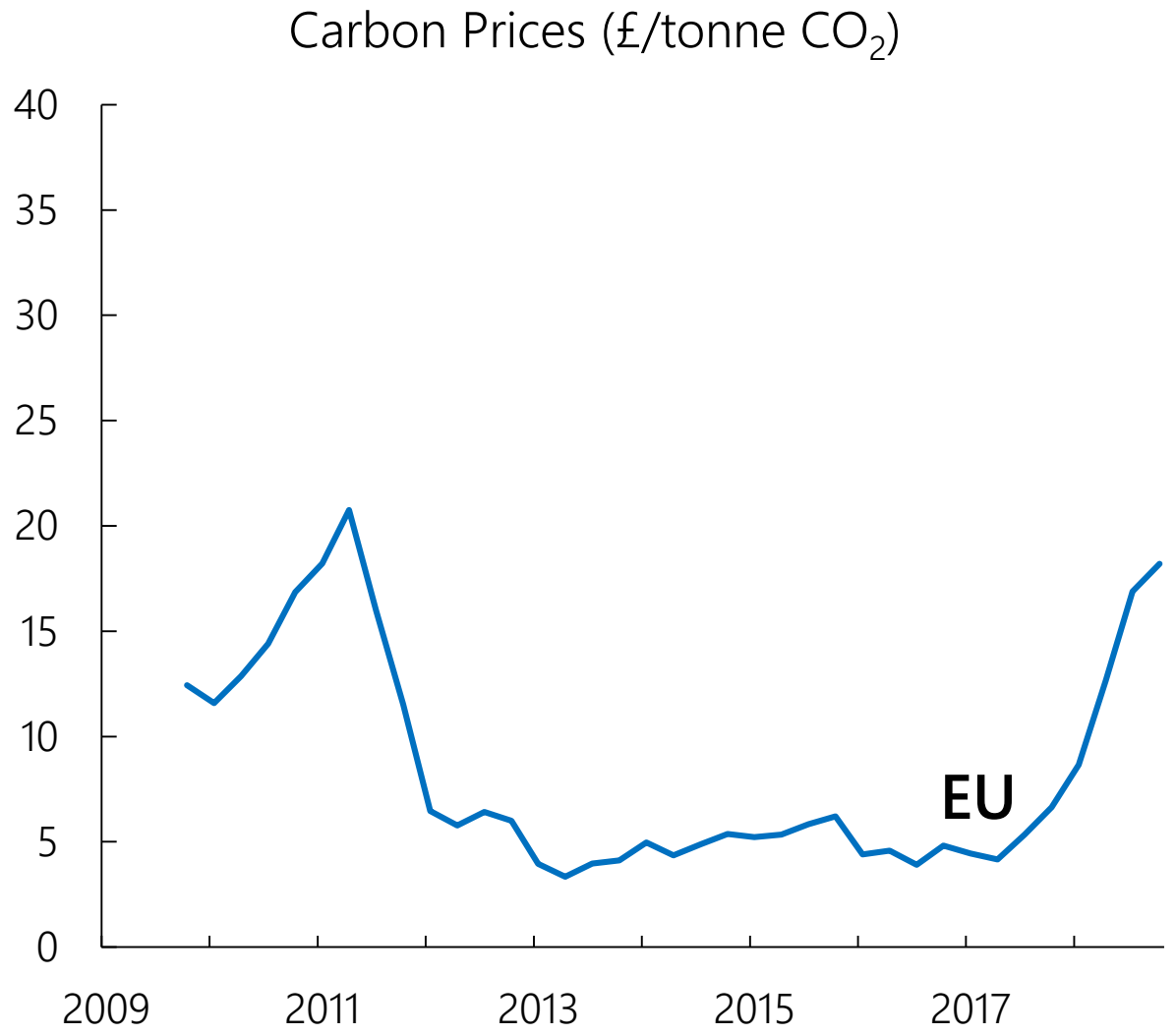

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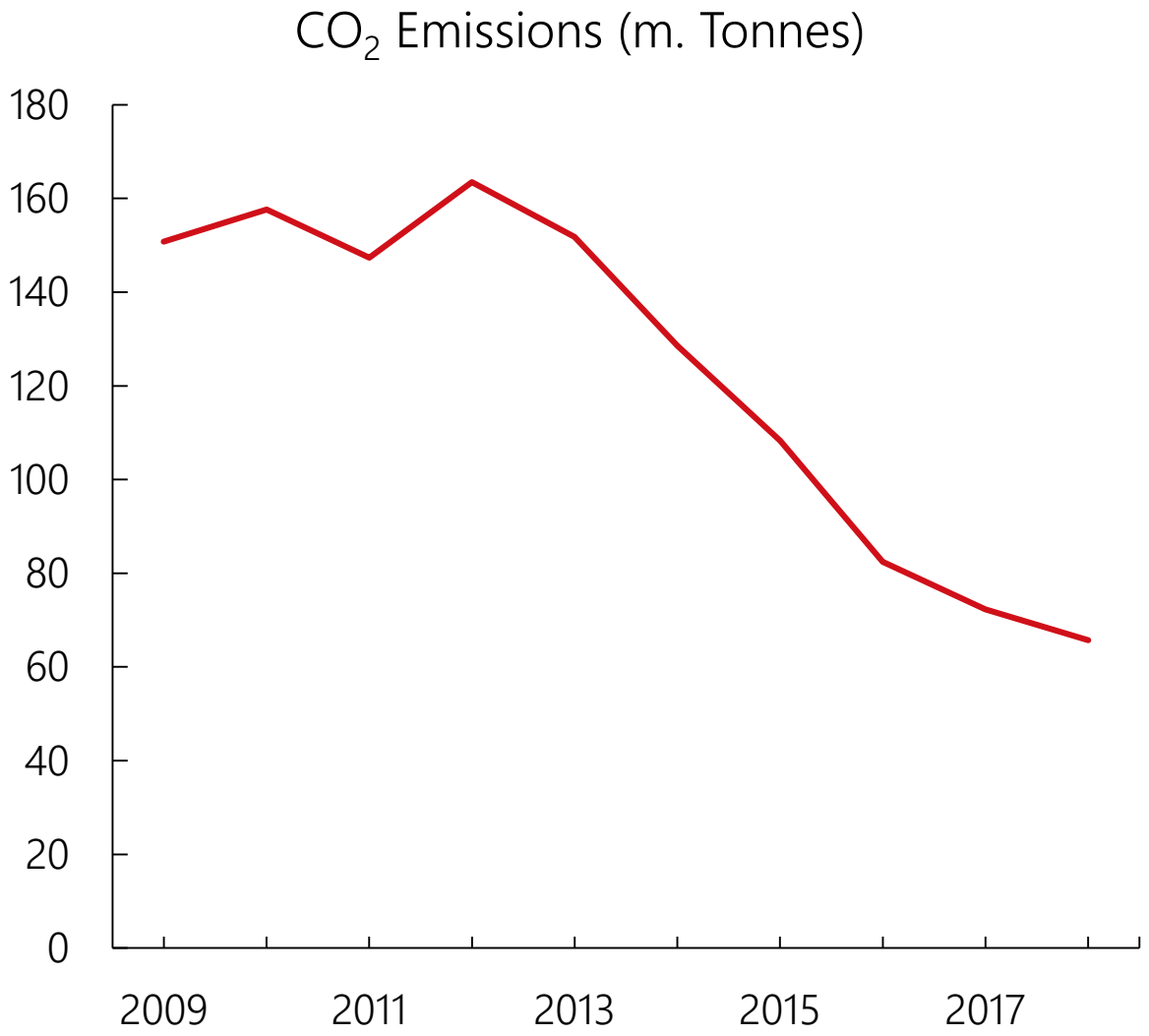

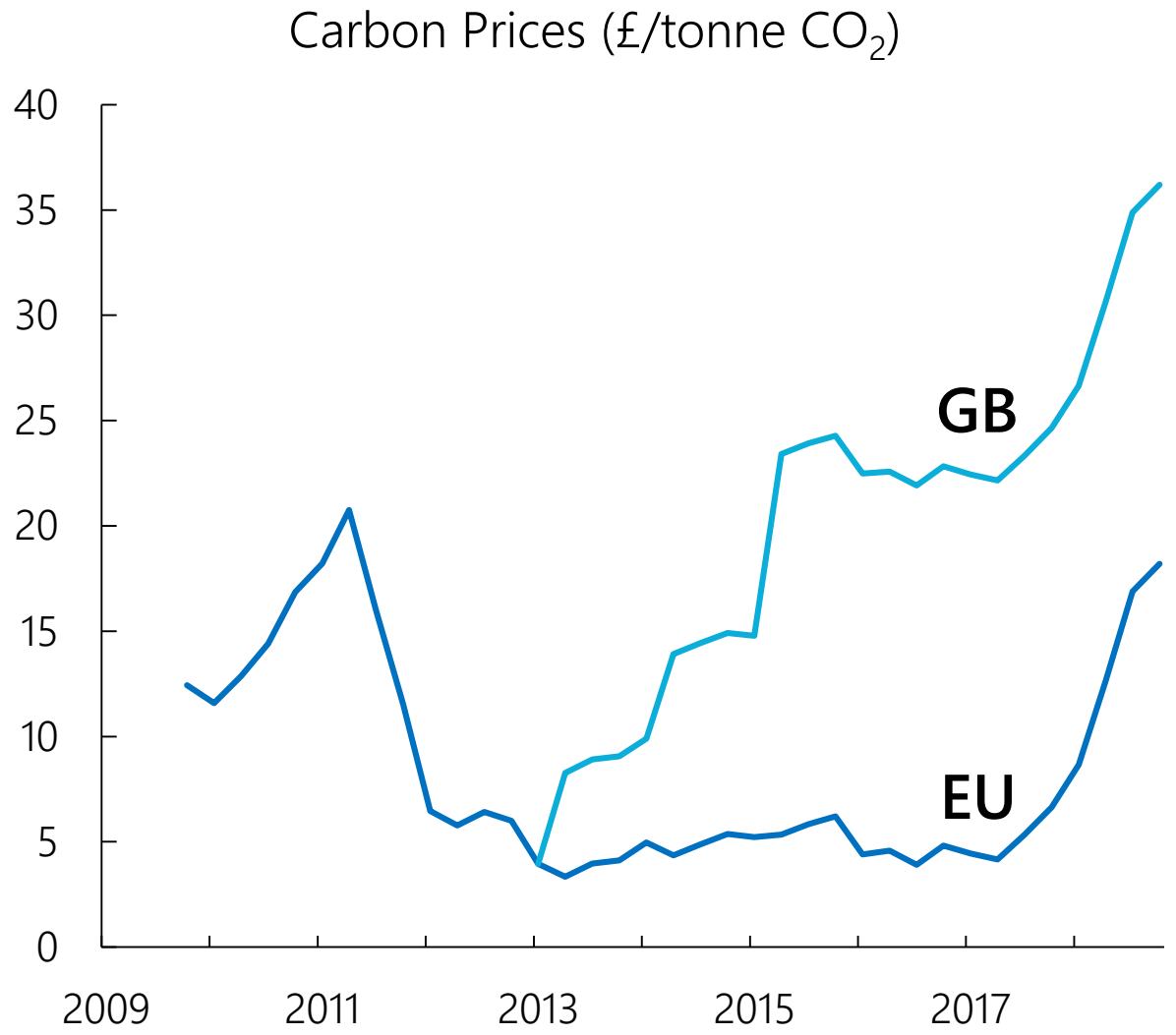

Source — Electric Insights, BEIS, ICE

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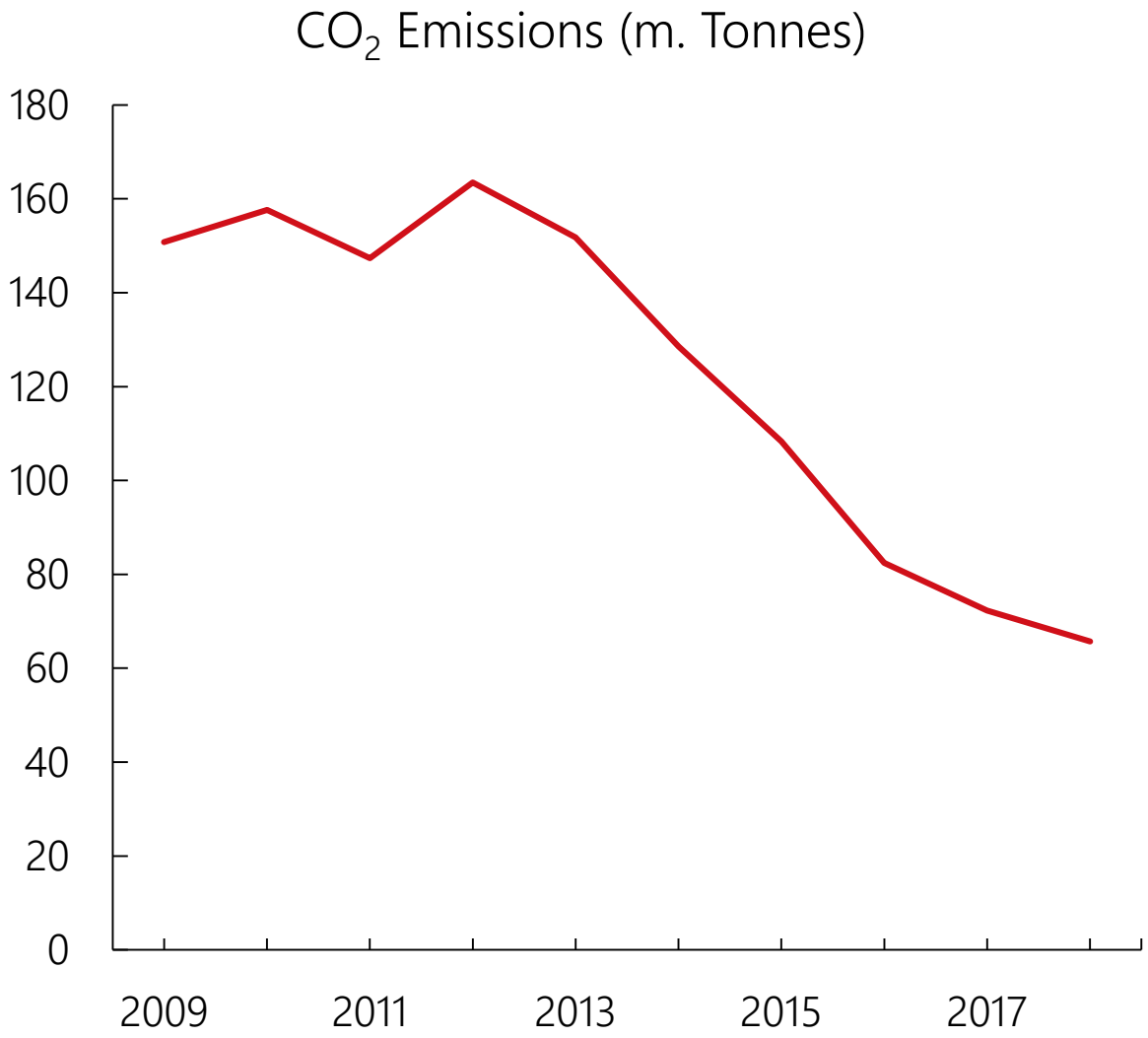

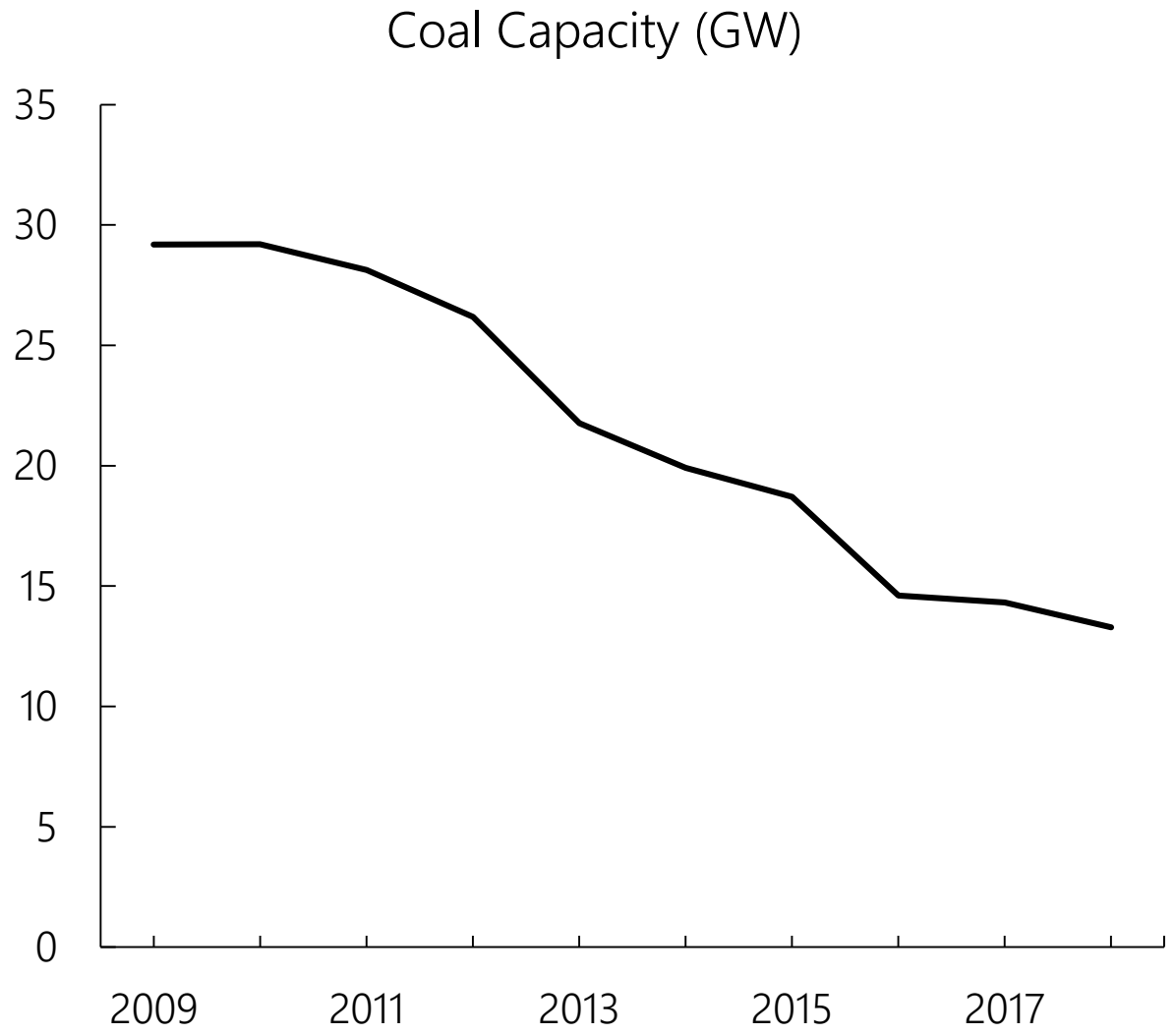

Source — Electric Insights

Britain’s generation mix

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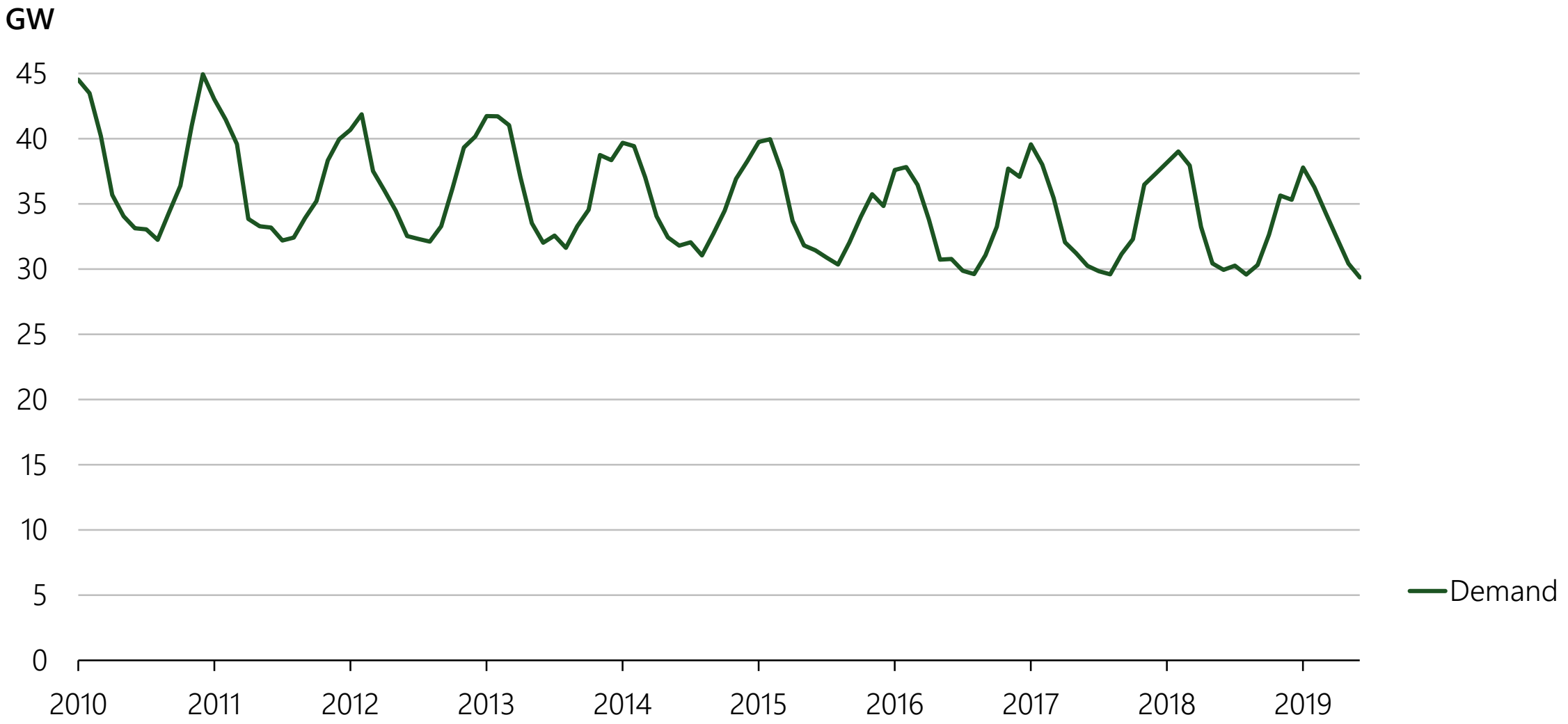

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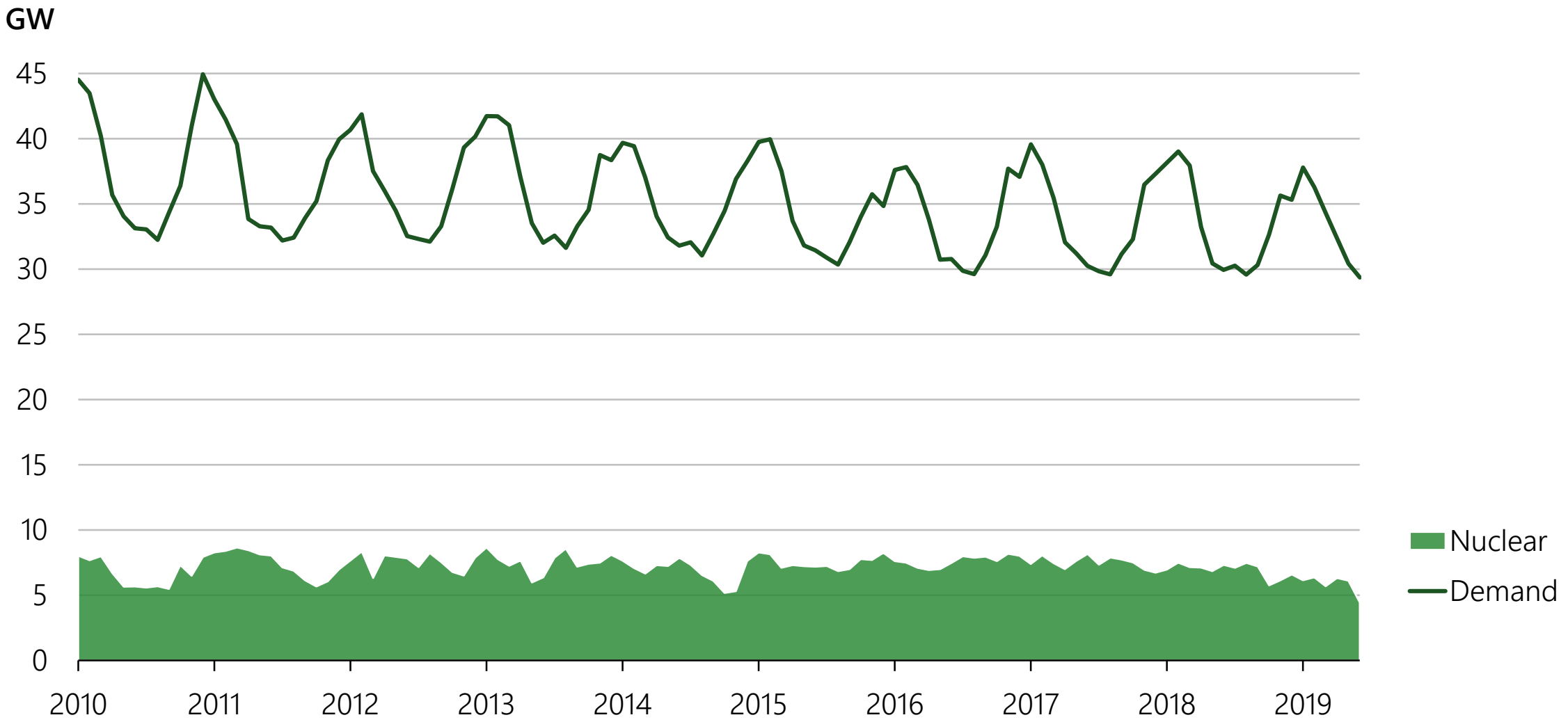

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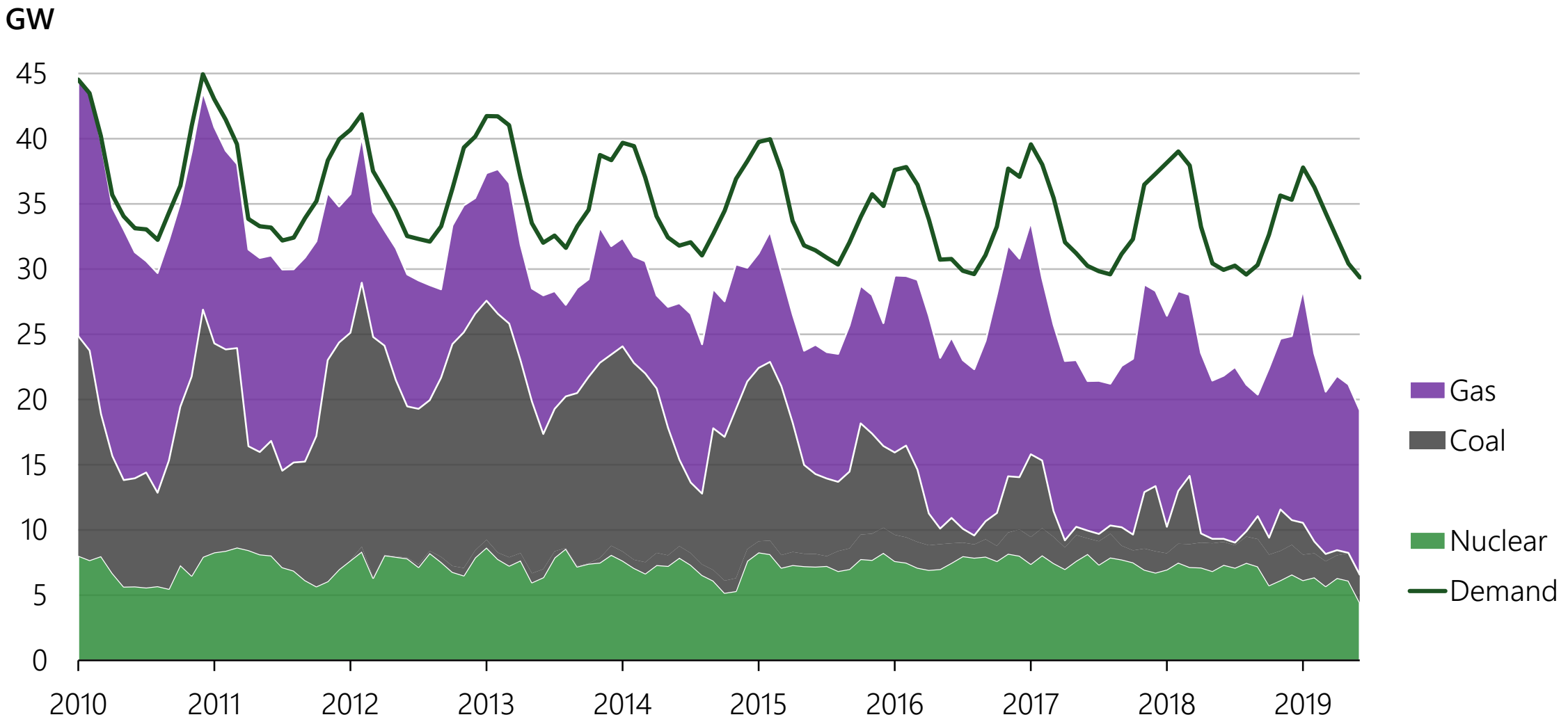

Source — Electric Insights

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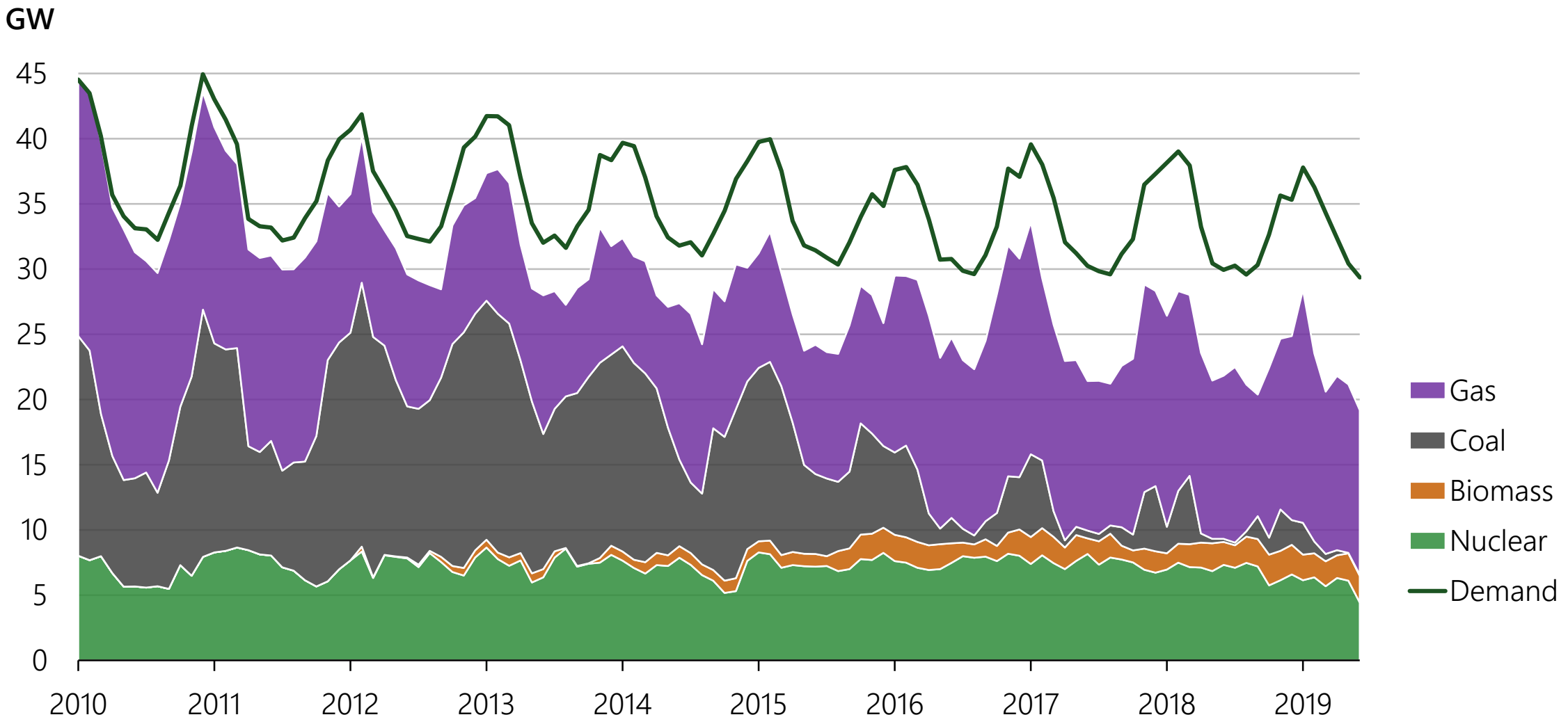

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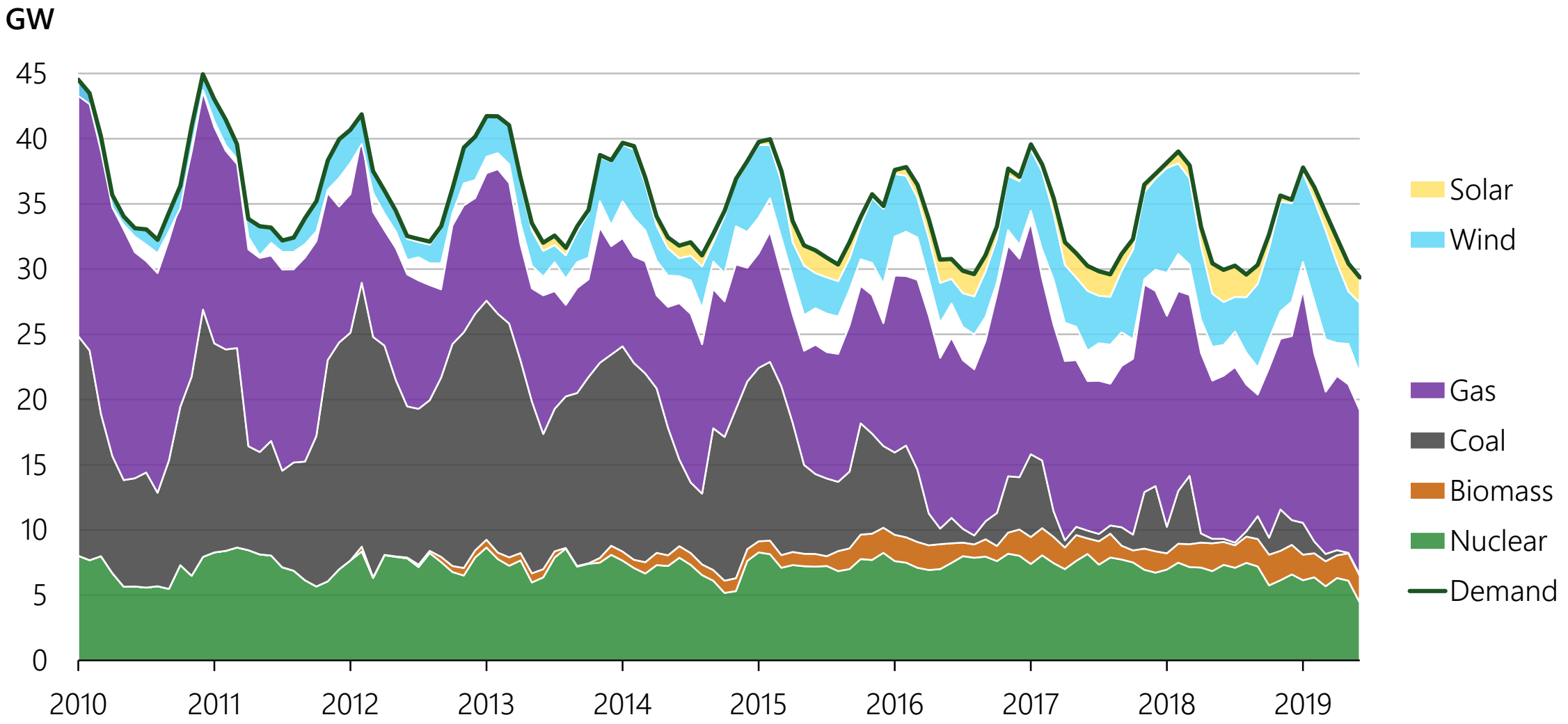

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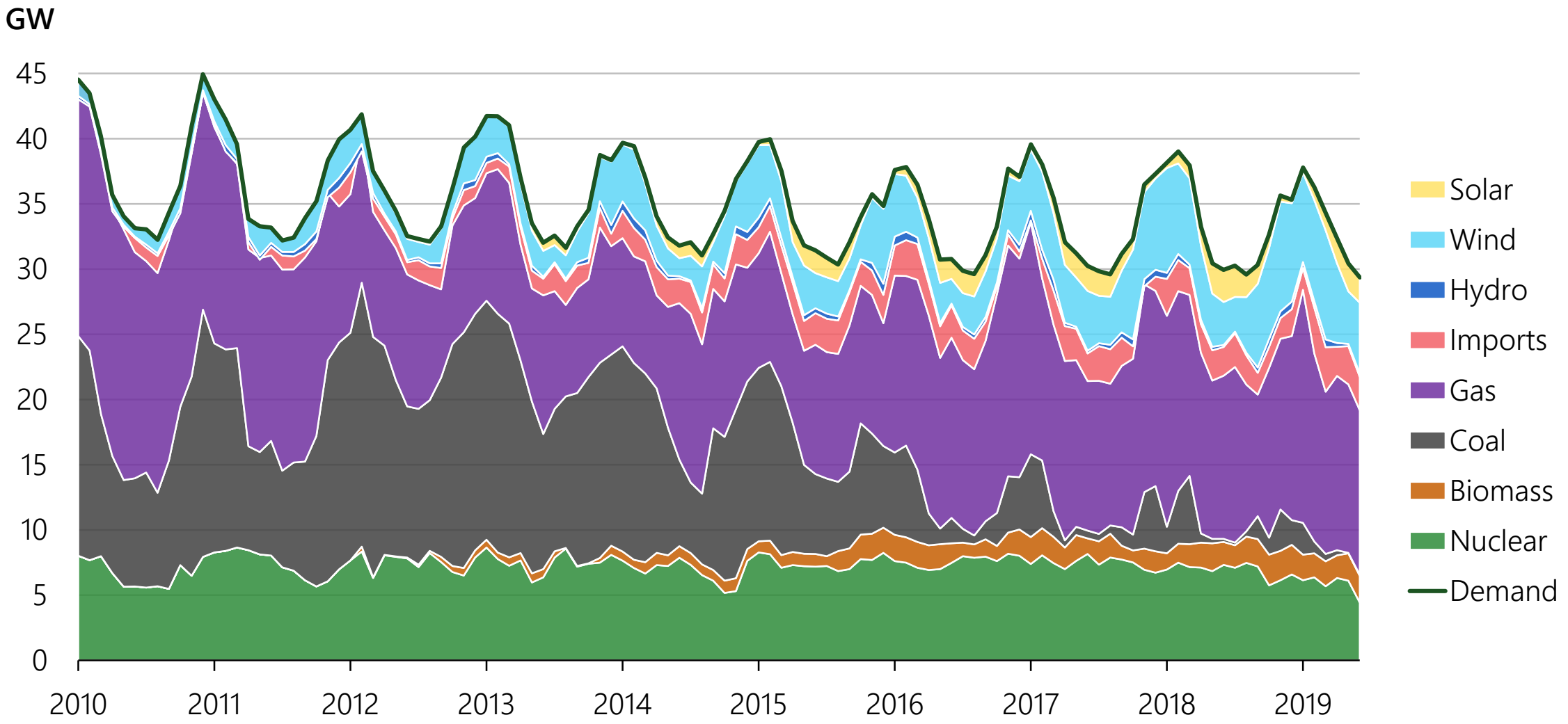
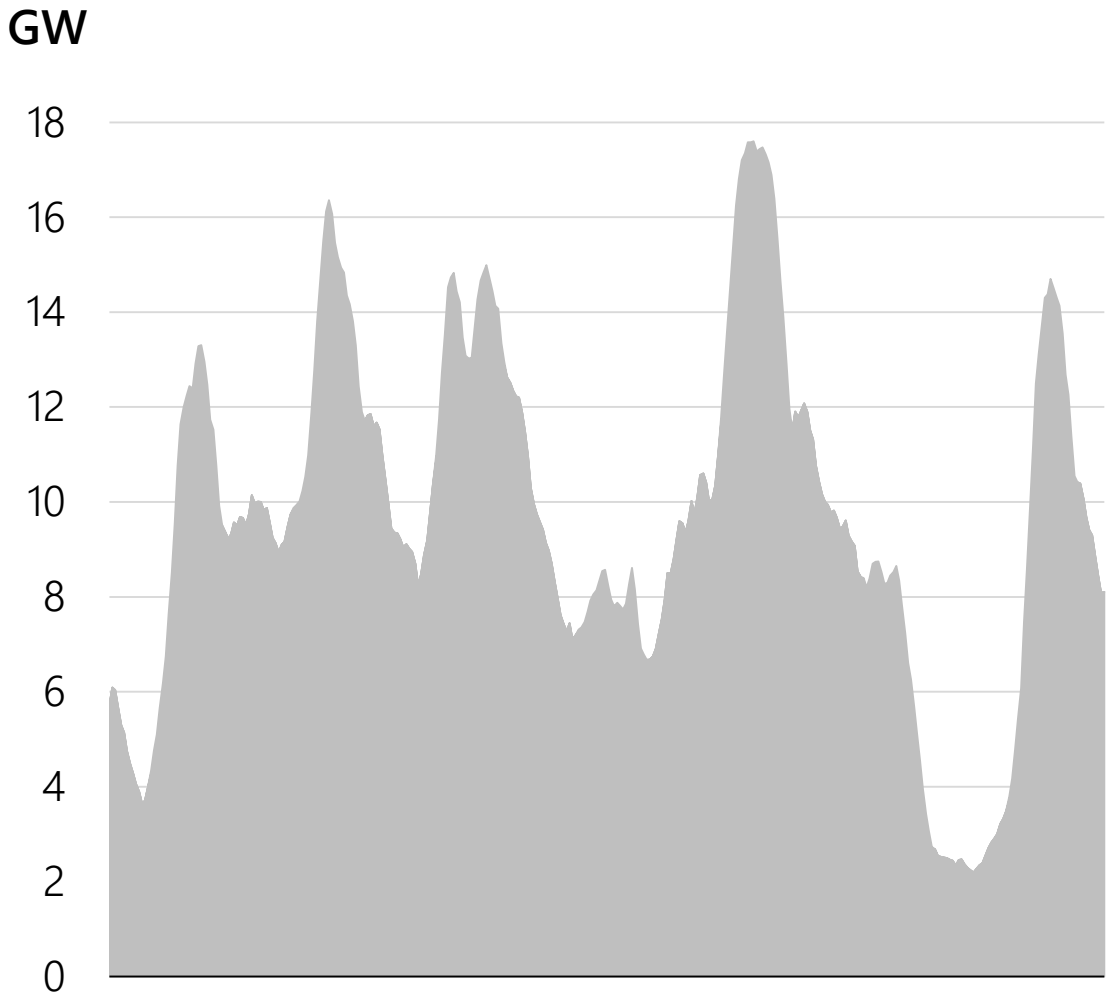
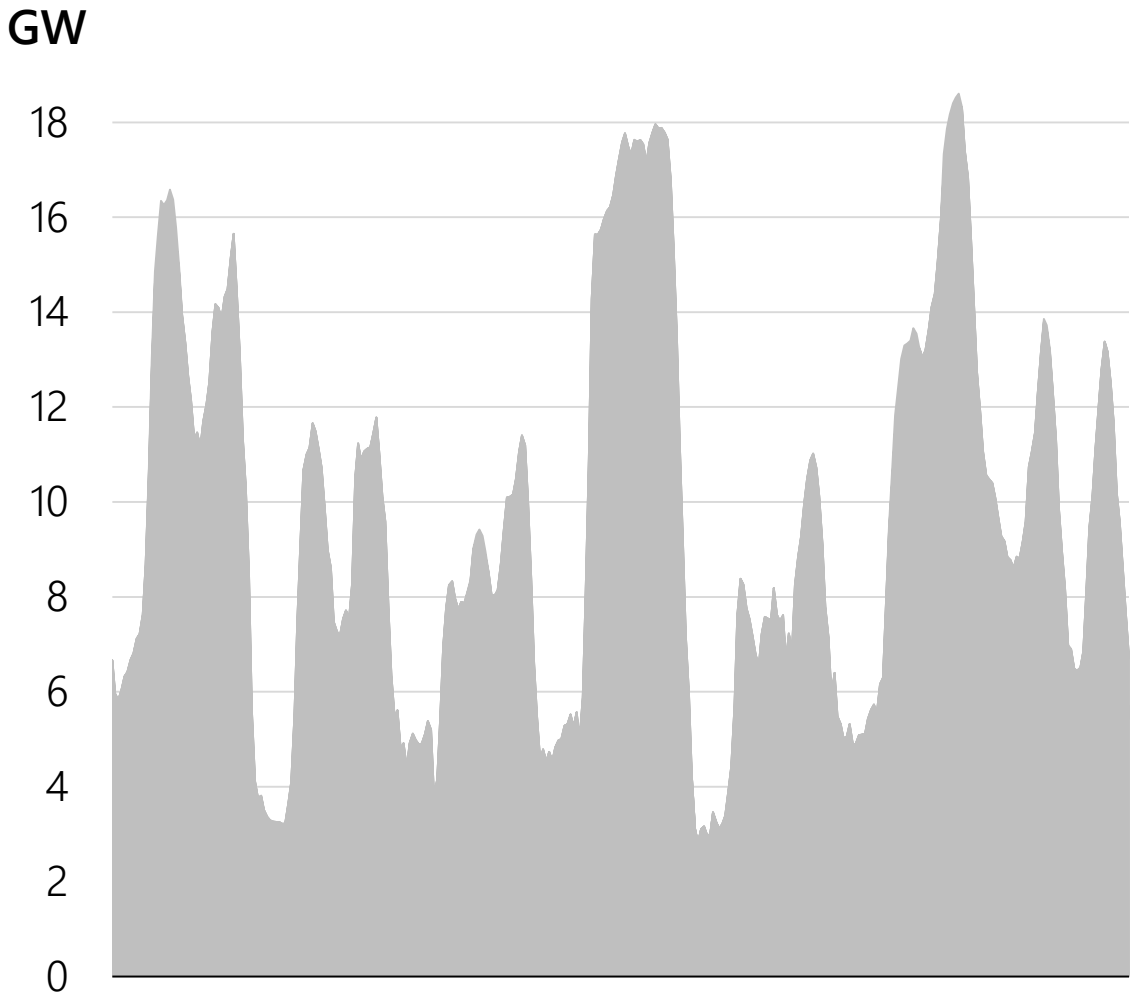


Source — Electric Insights

Coal, gas and oil vs. wind and solar





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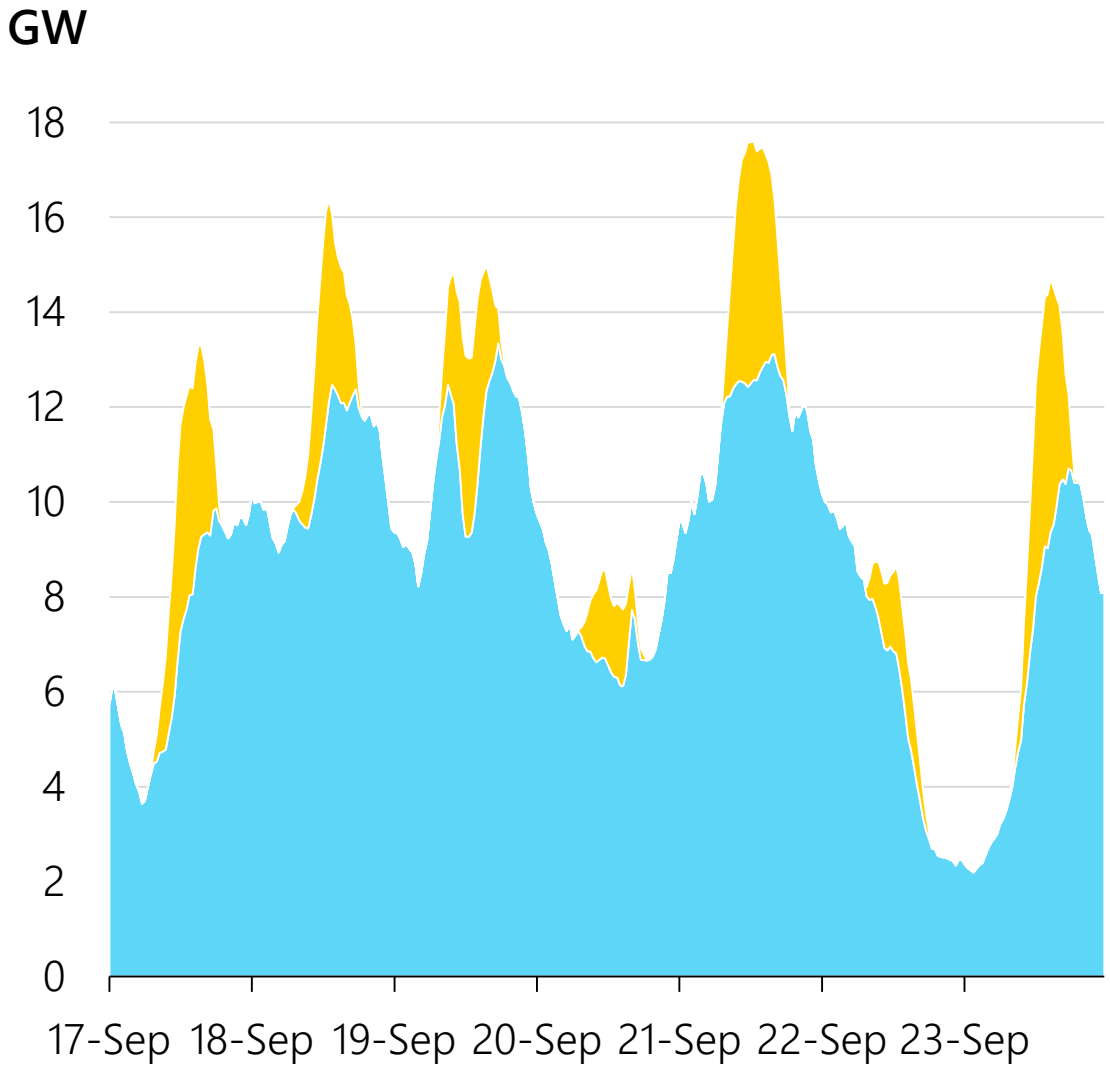

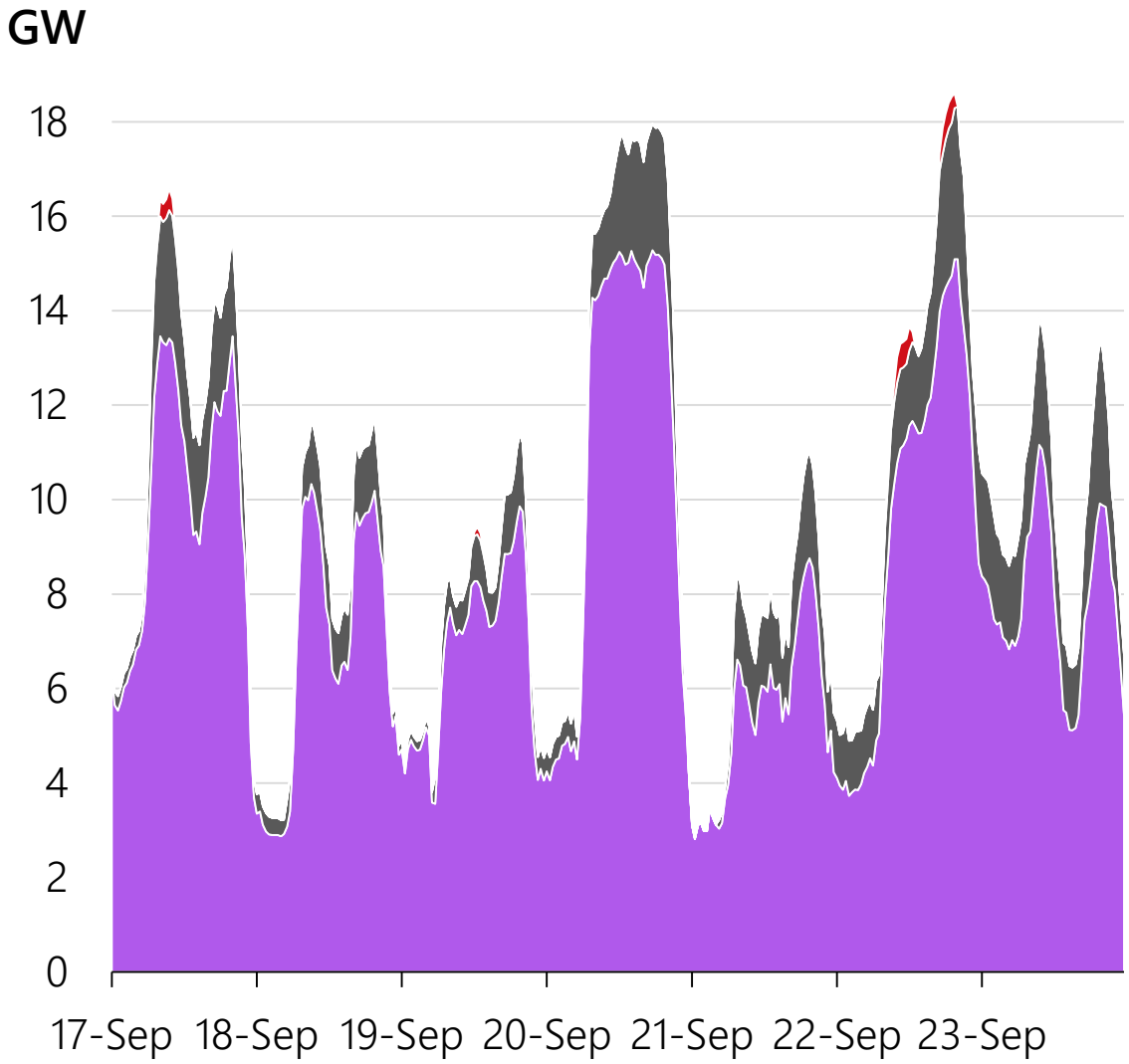

Source — Electric Insights

The power of carbon prices

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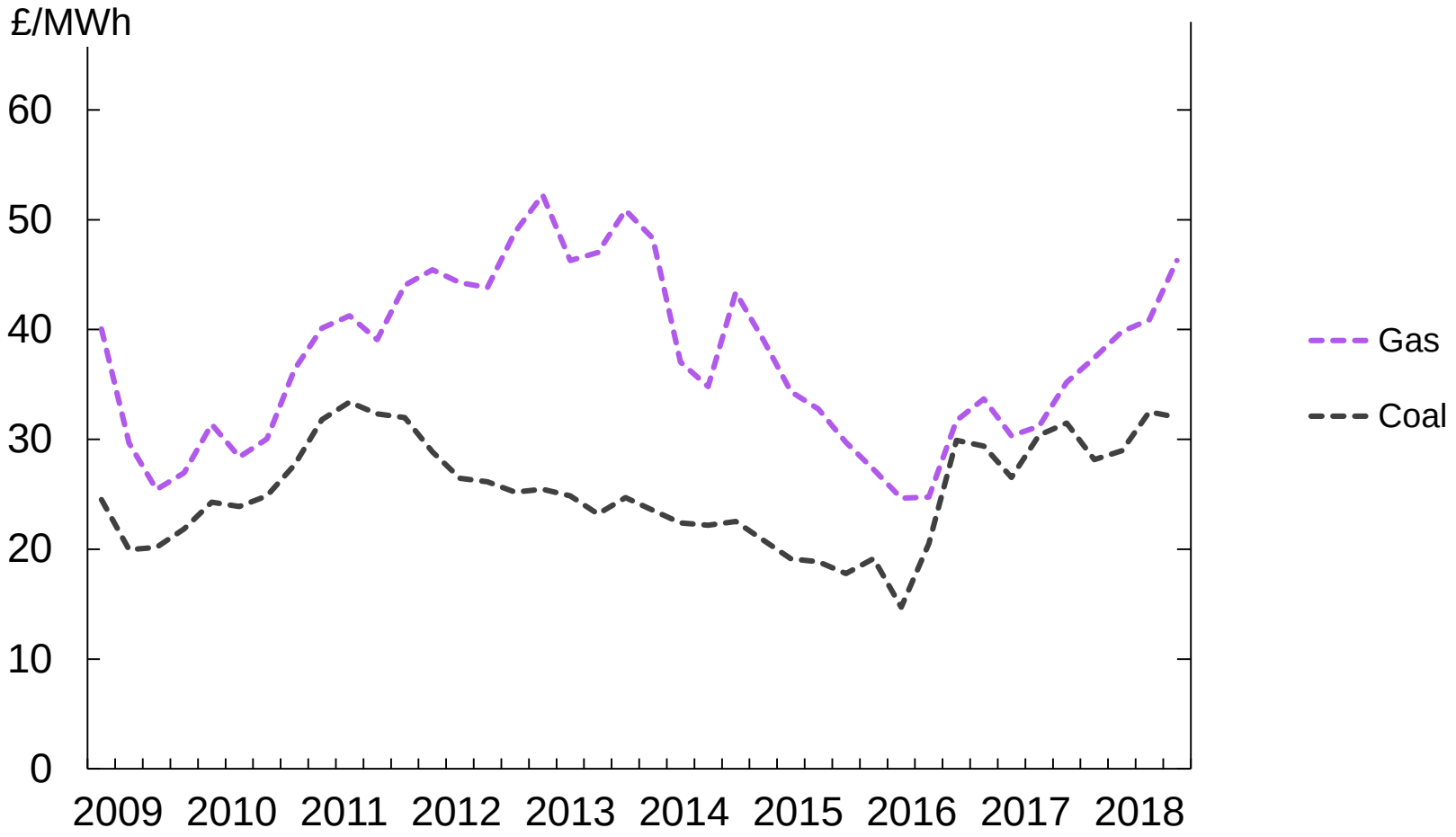
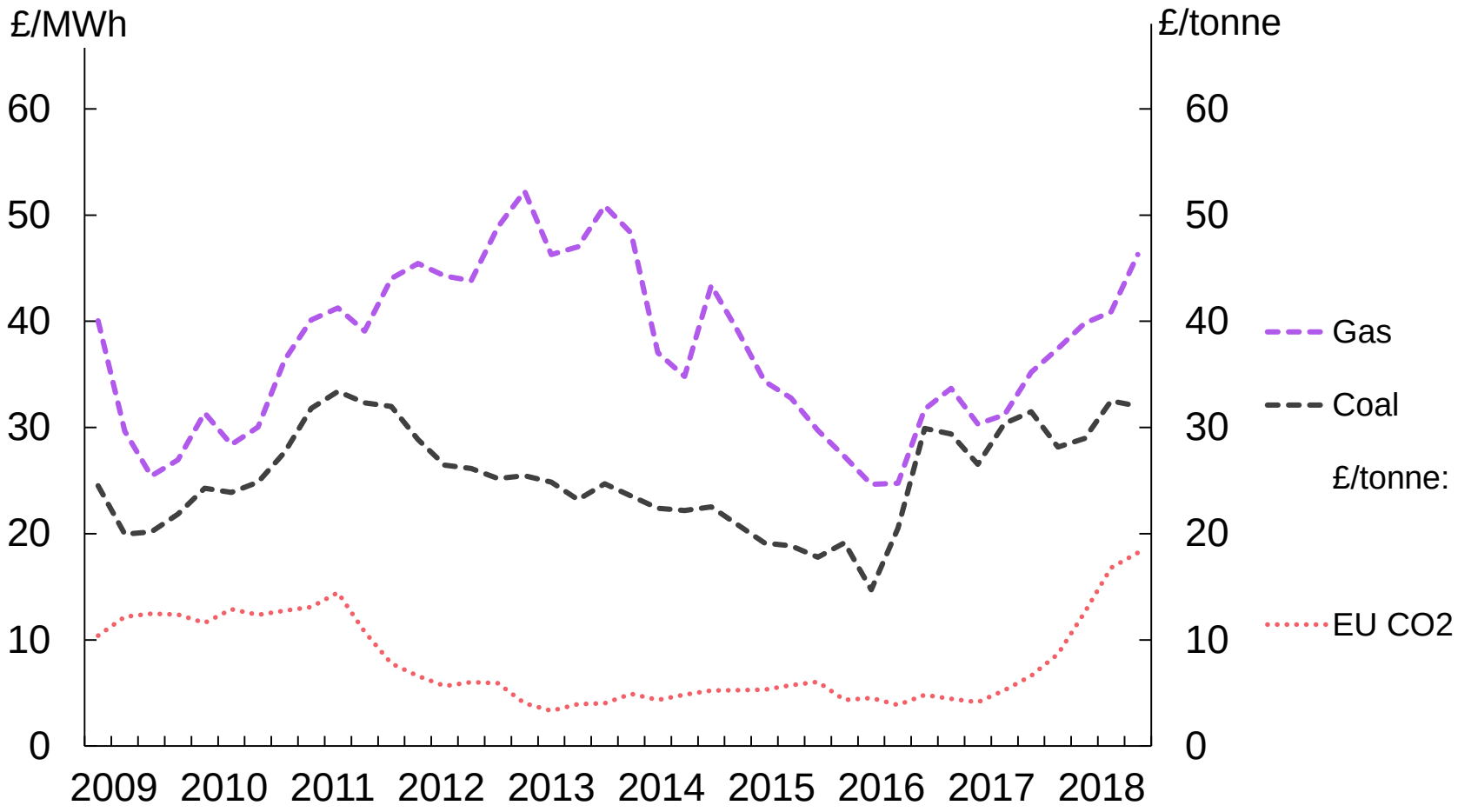


Fuel prices are for the amount needed per MWh of electricity output at typical efficiency

Source — BEIS, Elexon, ICE

The power of carbon prices



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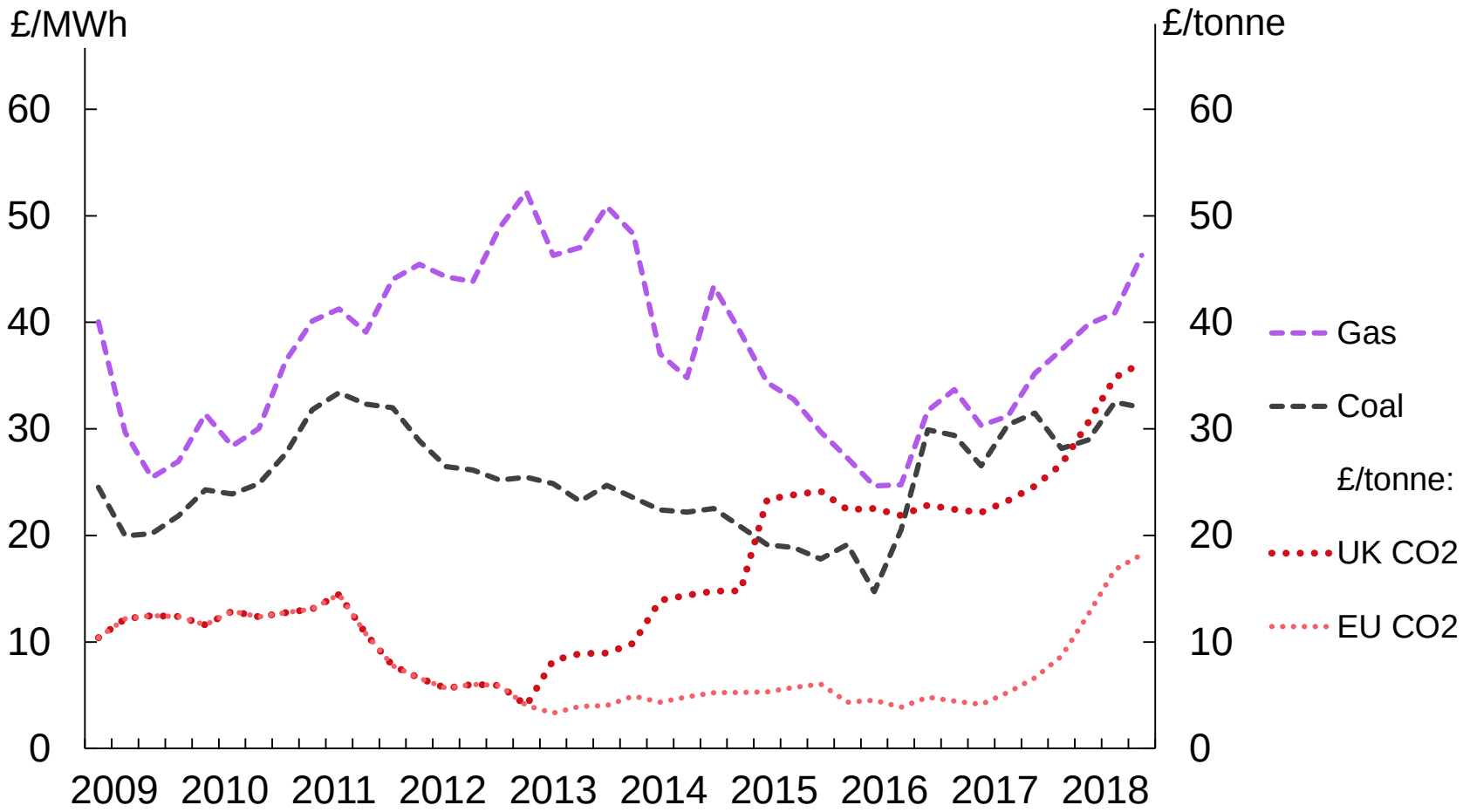

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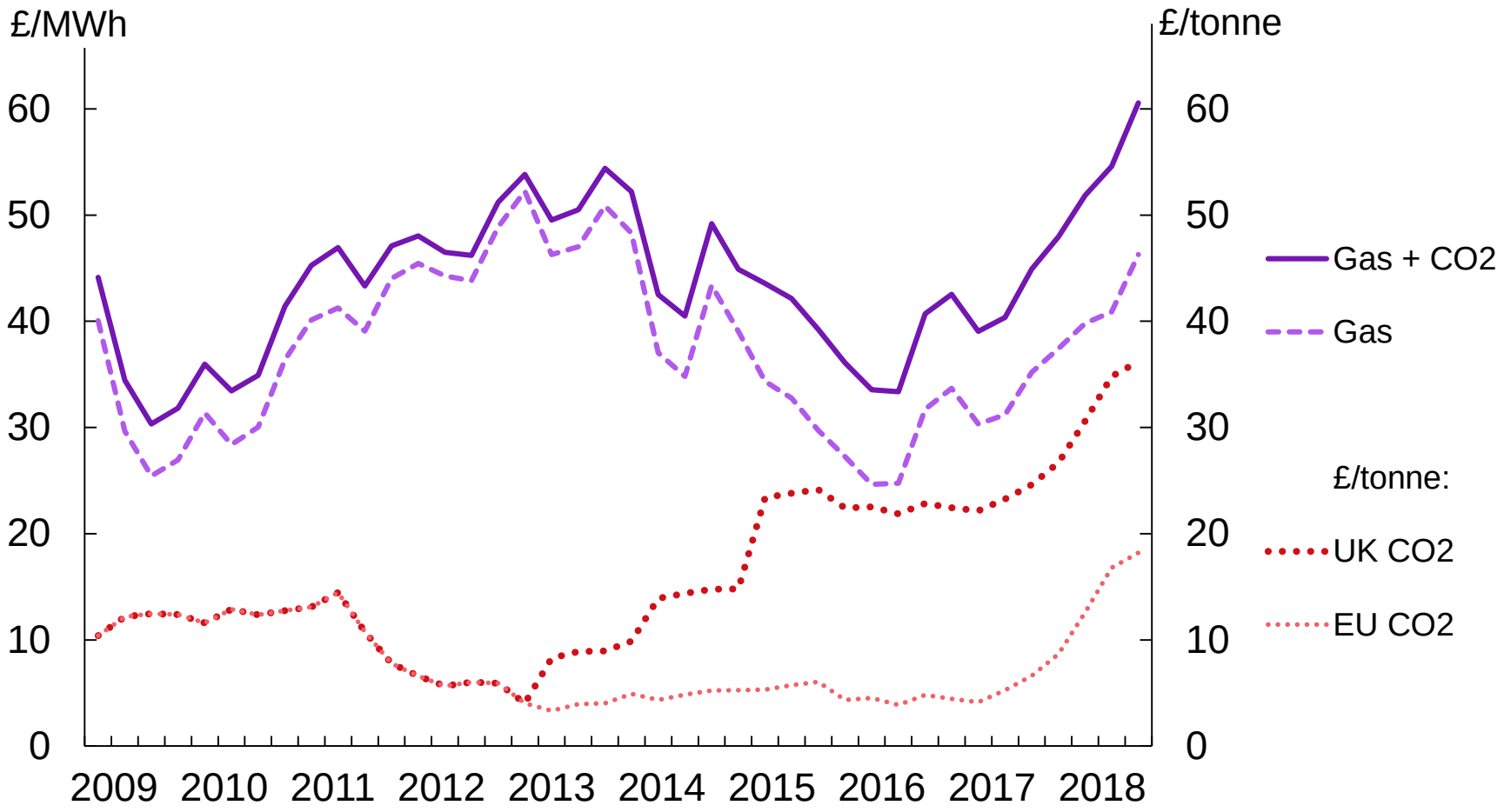

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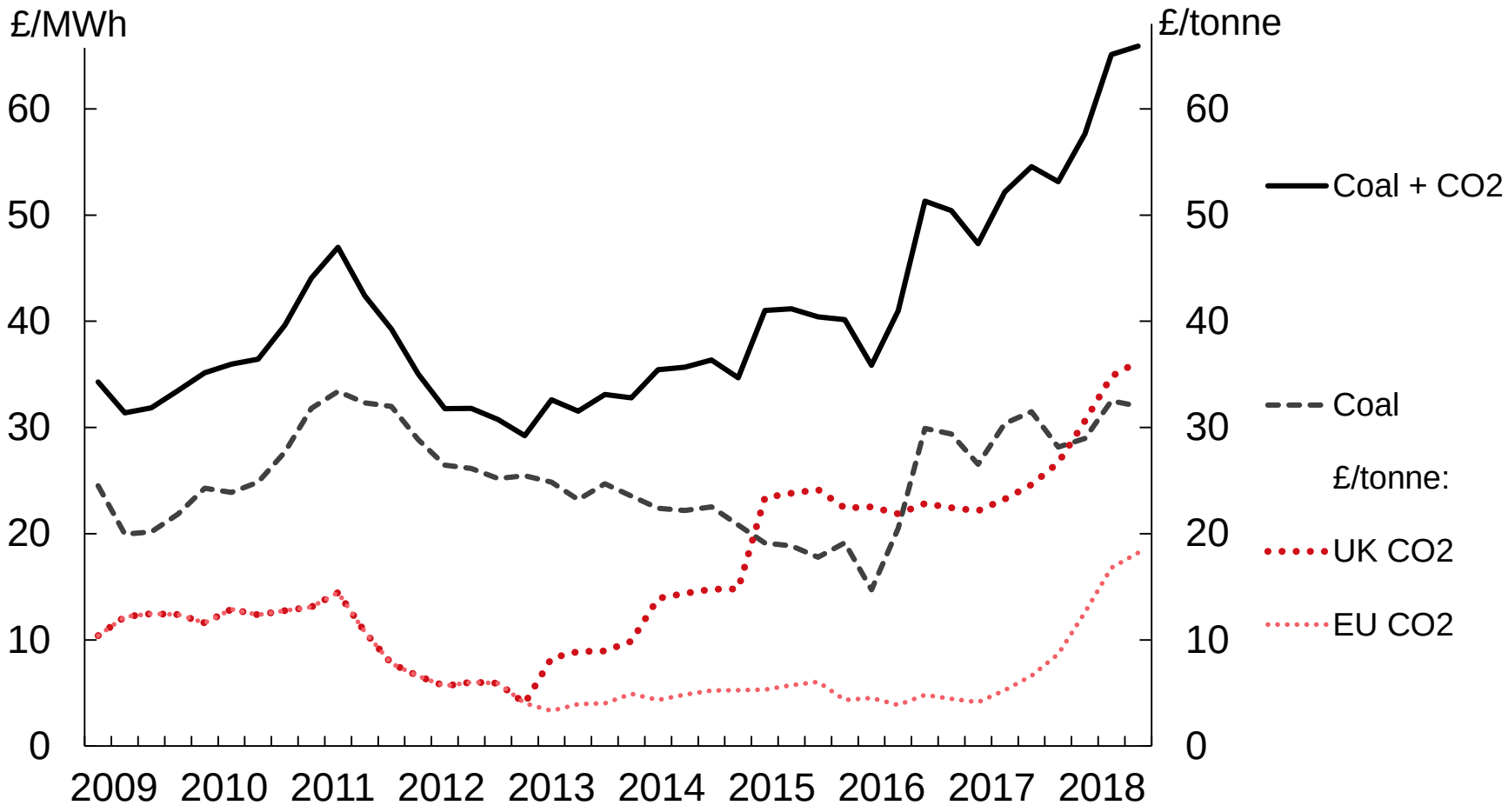

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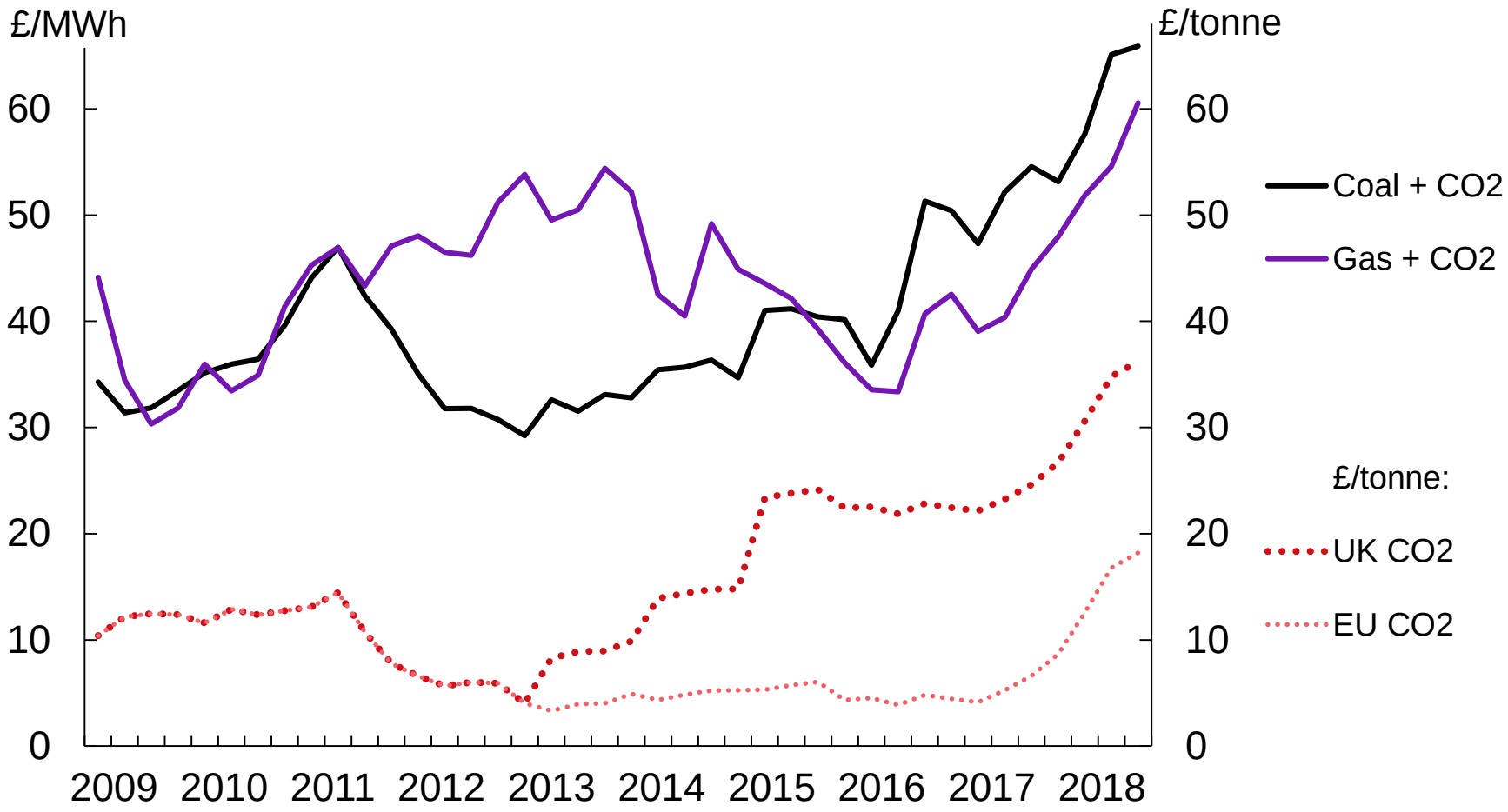

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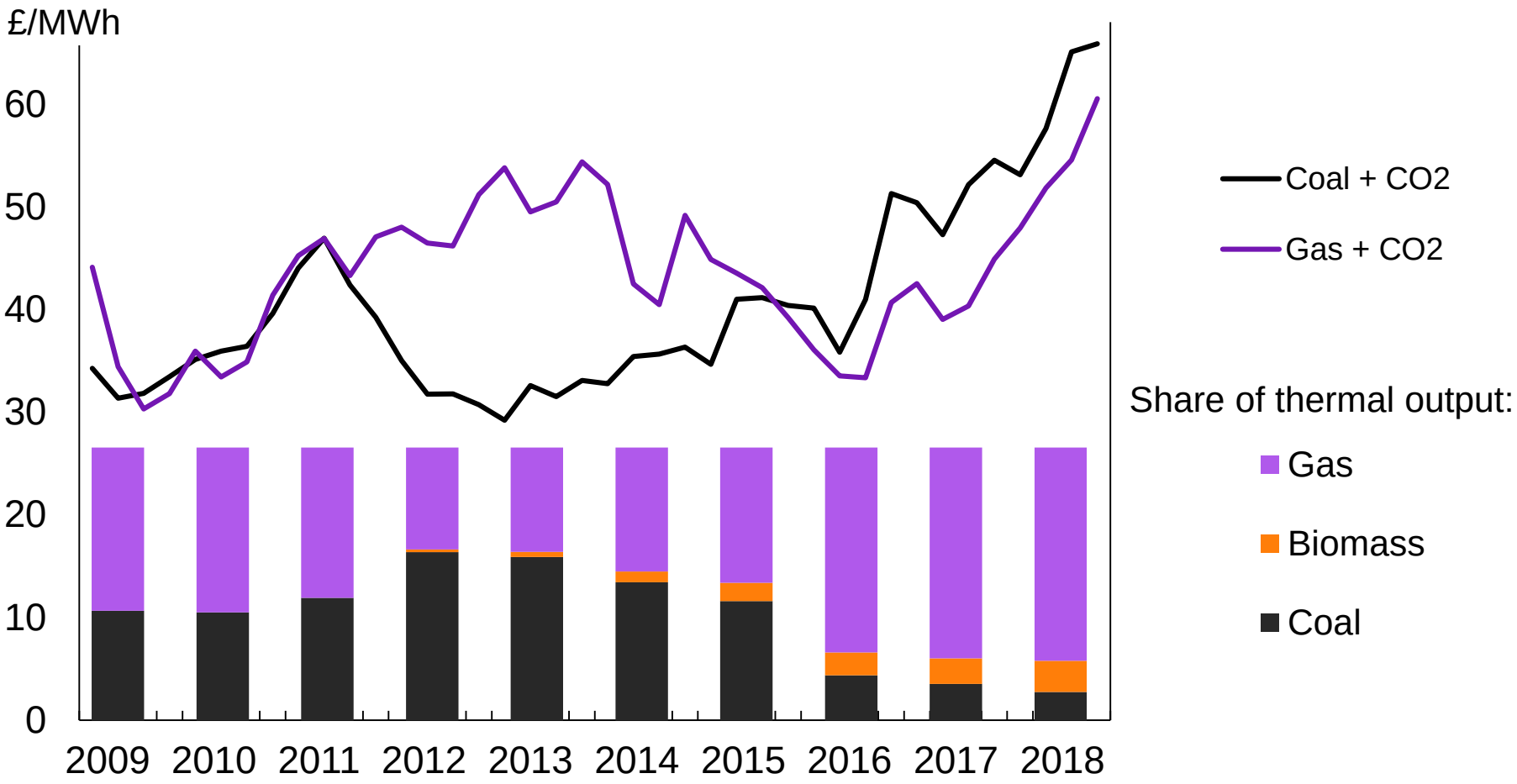

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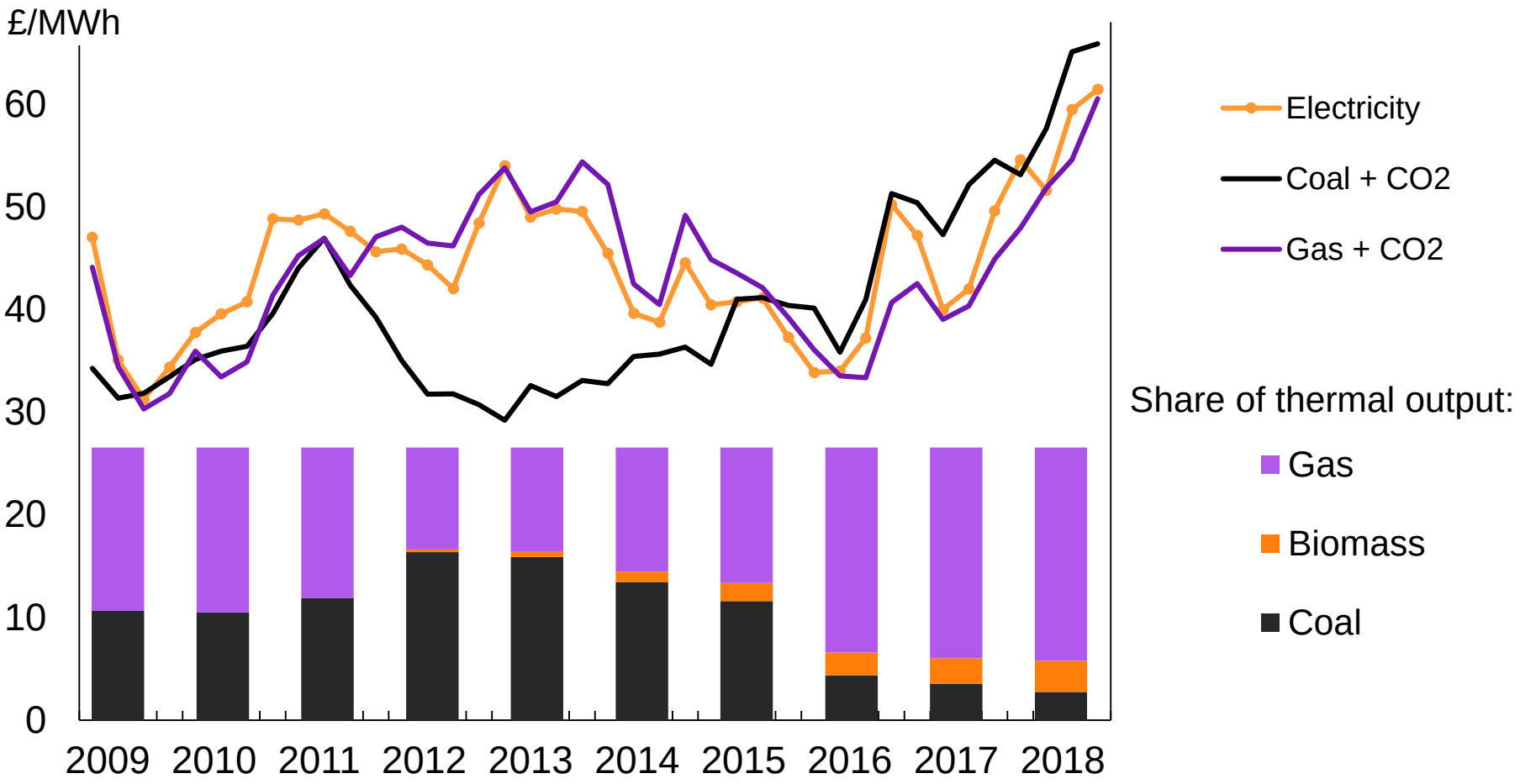


Fuel prices are for the amount needed per MWh of electricity output at typical efficiency

Source — BEIS, Elexon, ICE

Previous studies

Previous studies

Who?	Where?	What?	How Much?	Reference
Hawkes	Great Britain	Demand	690 kg/MWh	Energy Policy, 2010
Siler-Adams *et al.*	United States	Demand	490-830 kg/MWh *(vary over place)*	Environ. Sci. Technol., 2012
Kaffine *et al.*	Texas	Wind	470 kg/MWh	Energy Journal, 2013
Cullen	Texas	Wind	429 kg/MWh 560 kg/MWh	AEJ: Econ. Pol., 2013
Thompson *et al.*	Great Britain	Demand Wind	490-660 kg/MWh 483-611 kg/MWh *(vary over time)*	Energy Policy, 2017
Chyong *et al.*	Great Britain	Wind	334-436 kg/MWh *(vary over time)*	EPRG working paper, 2019

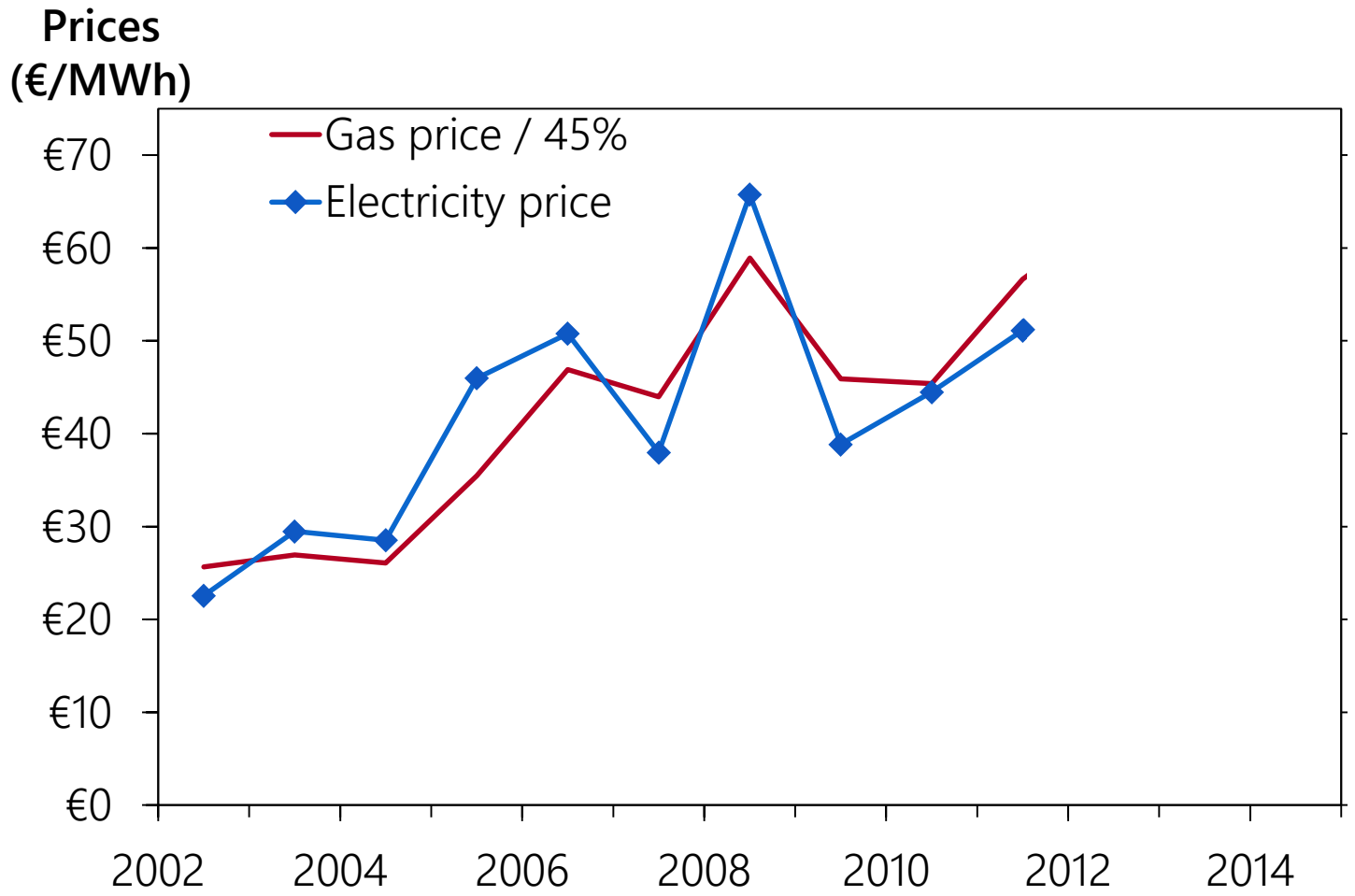
Renewables and prices

- The Merit Order Effect
  - Renewable output depresses prices until capacity adjusts
  - Sensfuß *et al.* (*Energy Policy*, 2008)
  - Sáenz de Miera *et al.* (*Energy Policy*, 2008)

- The Twomey-Neuhoff Effect
  - Renewable output depresses its own price
  - Twomey and Neuhoff (*Energy Policy*, 2010)

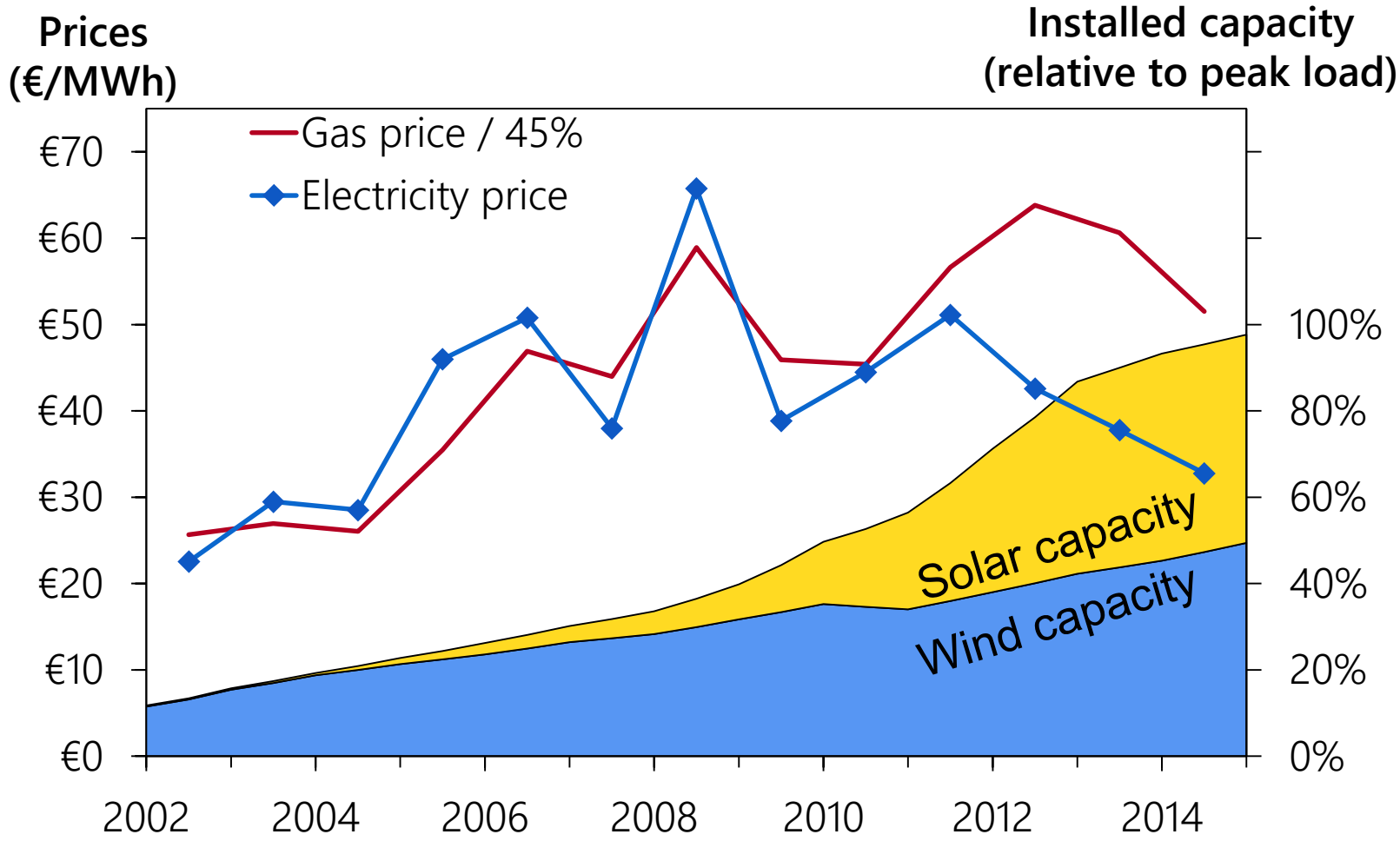
- The race between costs and revenues
  - Capacity gives learning, cutting costs; but revenues fall too!
  - Green and Léautier (*Toulouse WP*, 2015)

Germany's market



Source — Green, 2016, OxREP

Germany's market

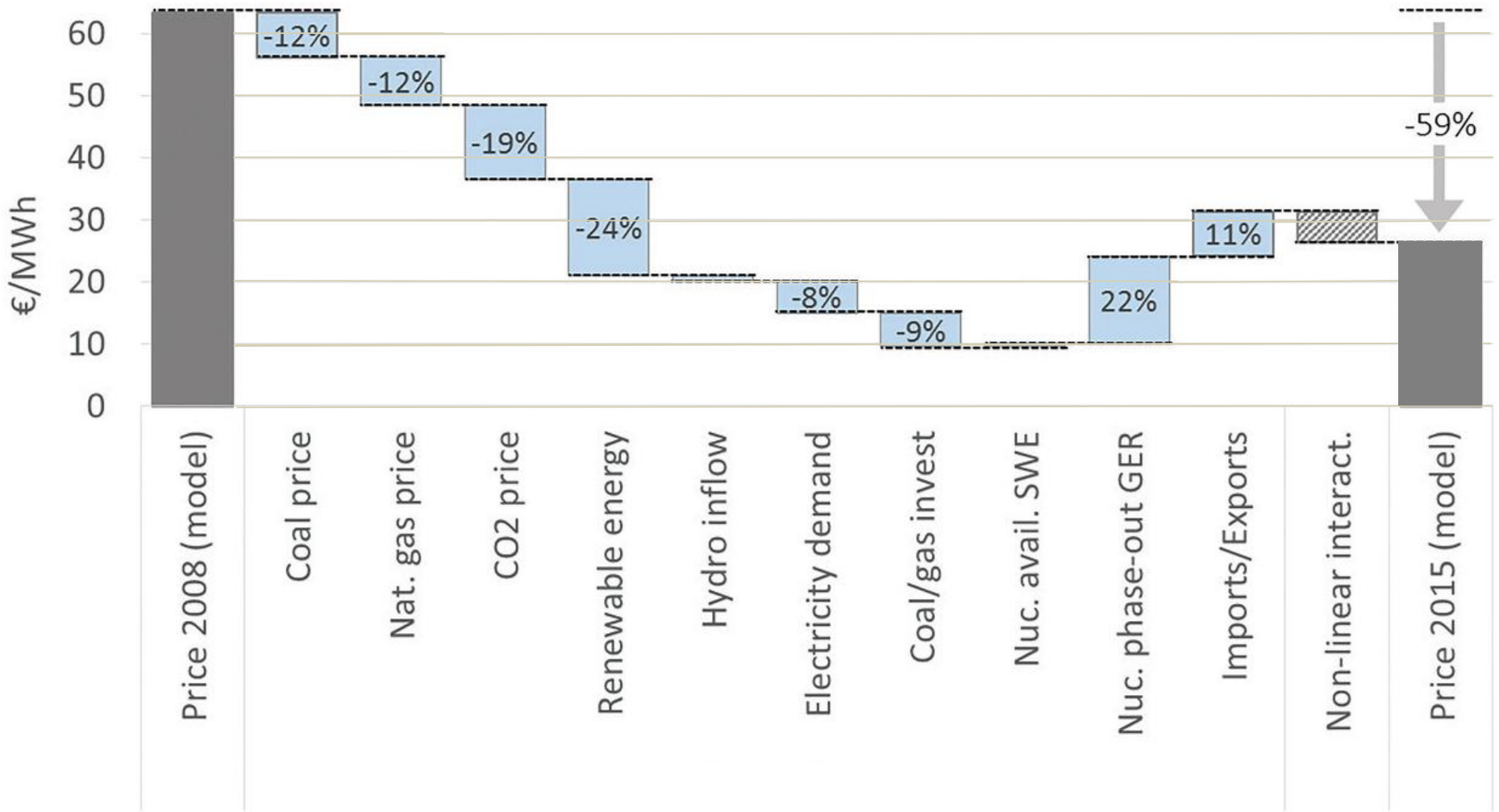


Source — Green, 2016, OxREP

German electricity prices

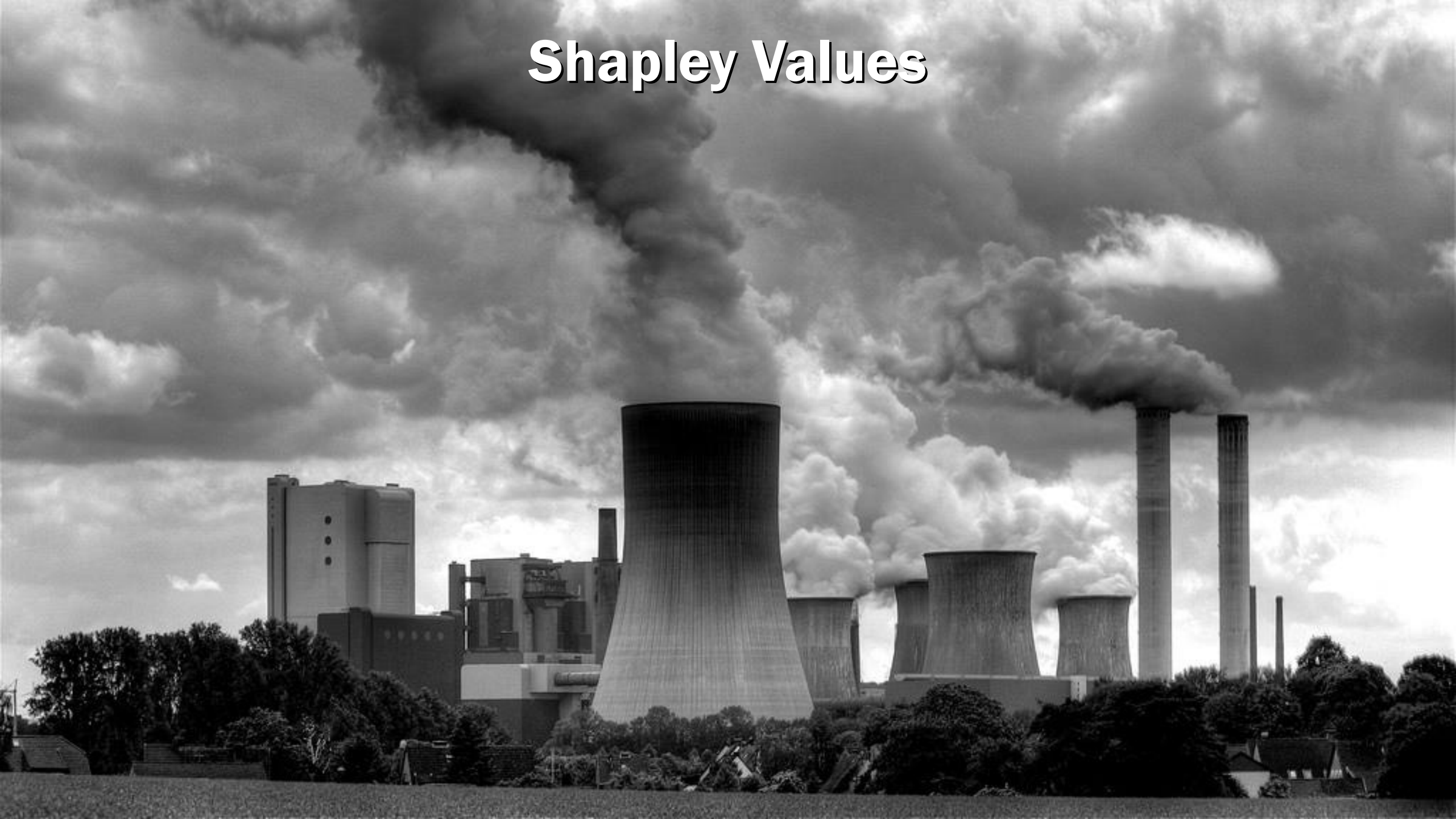
Source — Hirth, 2018, Energy Journal

German electricity prices



Source — Hirth, 2018, Energy Journal

Shapley Values



Shapley Values

- How much do you bring to a coalition?
  - Add yourself to every possible sub-coalition and take the average impact

- $\varphi_i(v)$ is the Shapley Value
- N players
- S is a potential coalition among them
- $v(S)$ is the worth of that coalition

$$\varphi_i(v) = \underbrace{\sum_{S \subseteq N \setminus \{i\}} \frac{|S|!\,(N - |S| - 1)!}{N!}}_{\text{weighting}} \underbrace{\big(v(S \cup \{i\}) - v(S)\big)}_{i\text{'s contribution}}$$

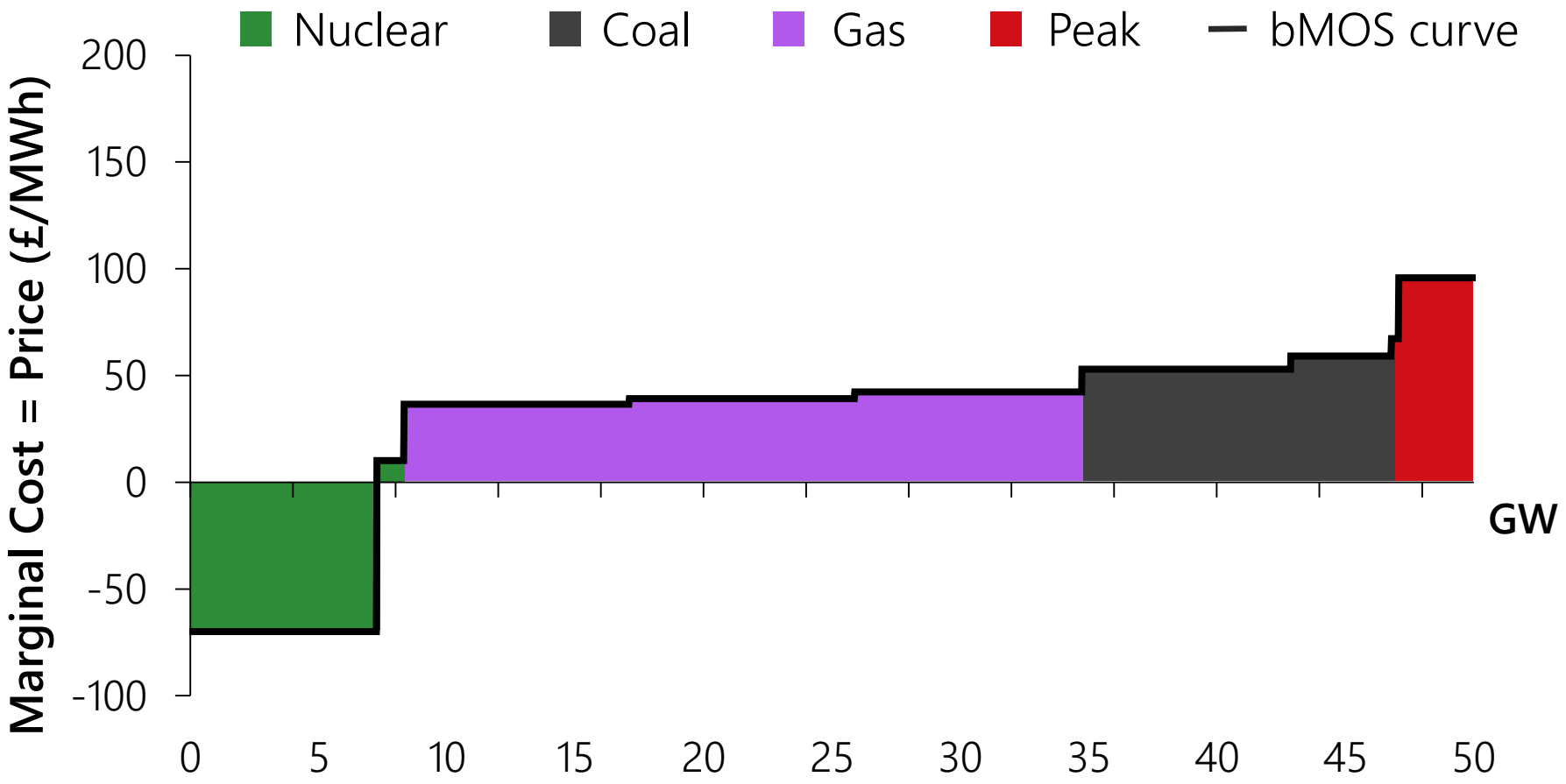
Shapley Values

- Applied to this ‘game’:
  - *Worth* is carbon emissions, which fell from 164 to 66 Mt.
  - *Worth* can also be electricity prices, which rose from £45 to £57 / MWh

- Coalitions are formed from:
  - Carbon price ⇗
  - Coal price ⇨ and gas price ⇨
  - Coal capacity ⇘ and gas capacity ⇨
  - Wind capacity ⇗ and solar capacity ⇗
  - Demand ⇘

Simulation: Enhanced Merit Order Stack

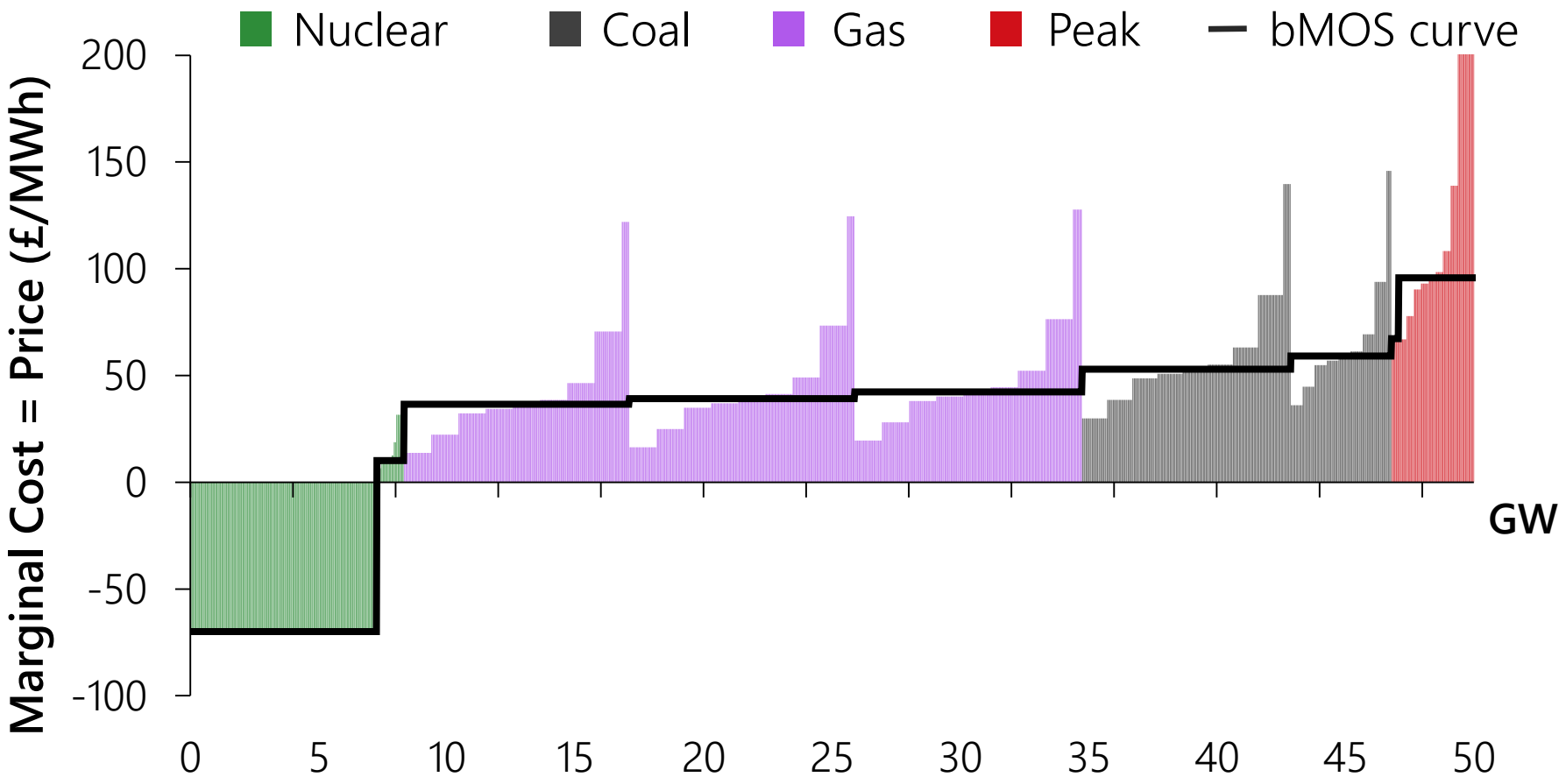
- A typical 'stack' model with blocks of plant:



Source — Ward, 2019, Energy Policy

Simulation: Enhanced Merit Order Stack

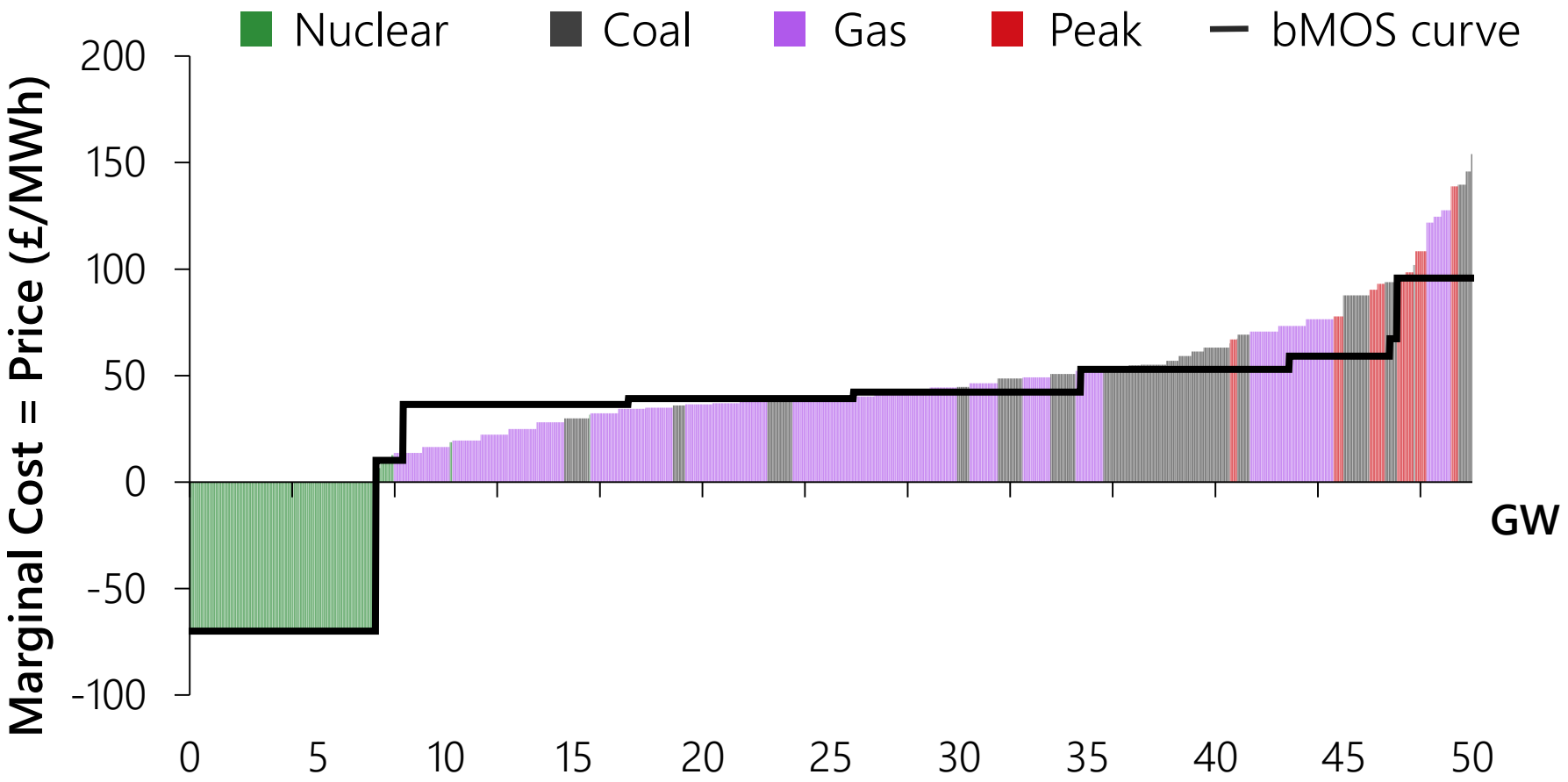
- Let each type of plant have tranches with different bids



Source — Ward, 2019, Energy Policy

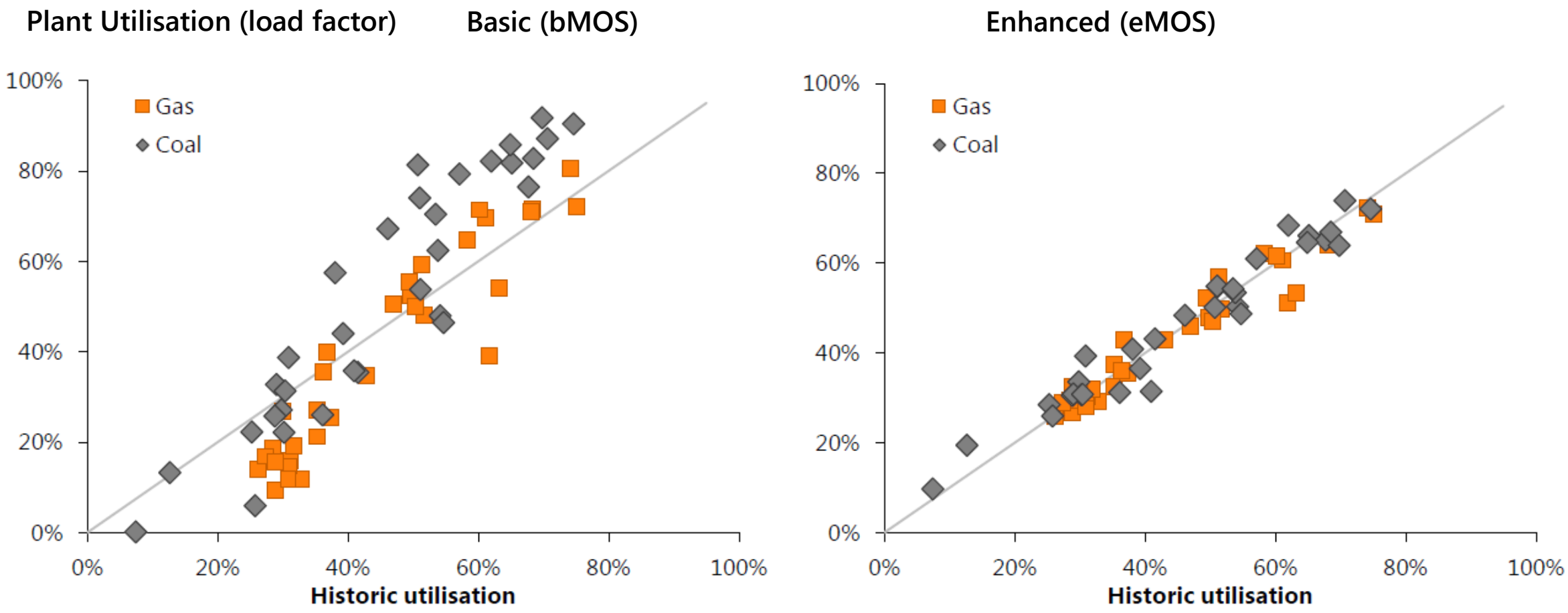
Simulation: Enhanced Merit Order Stack

- Re-sort those tranches to get a more natural supply curve:



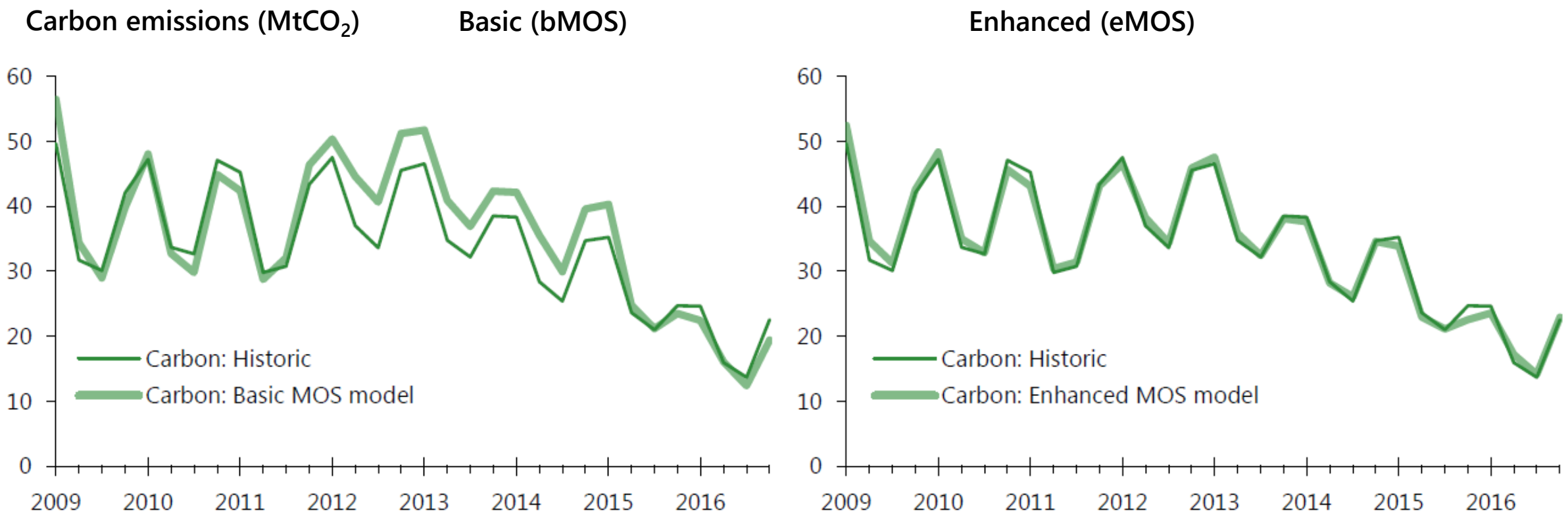
Source — Ward, 2019, Energy Policy

Simulation: Enhanced Merit Order Stack



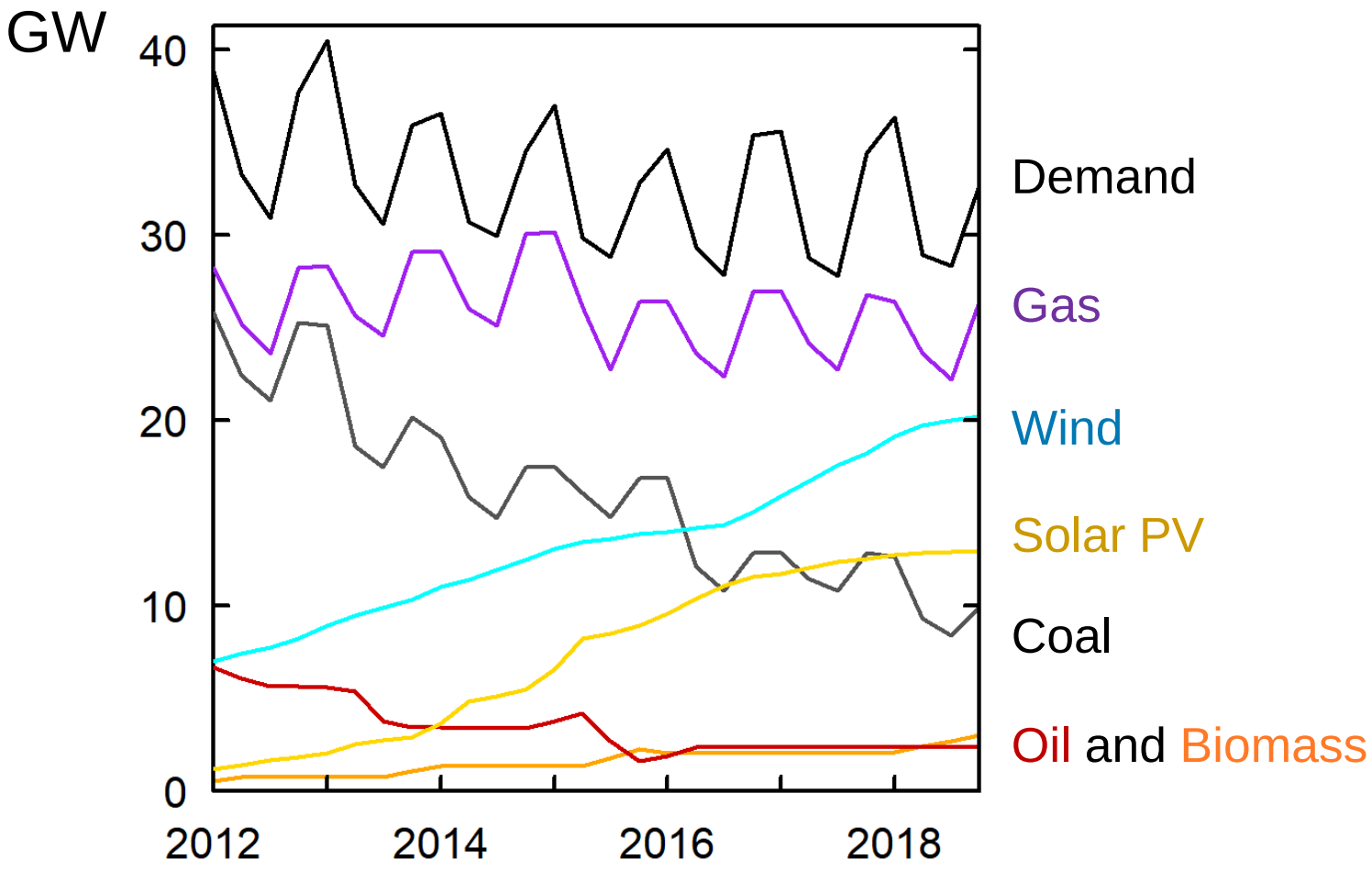
Source — Ward, 2019, Energy Policy

Simulation: Enhanced Merit Order Stack

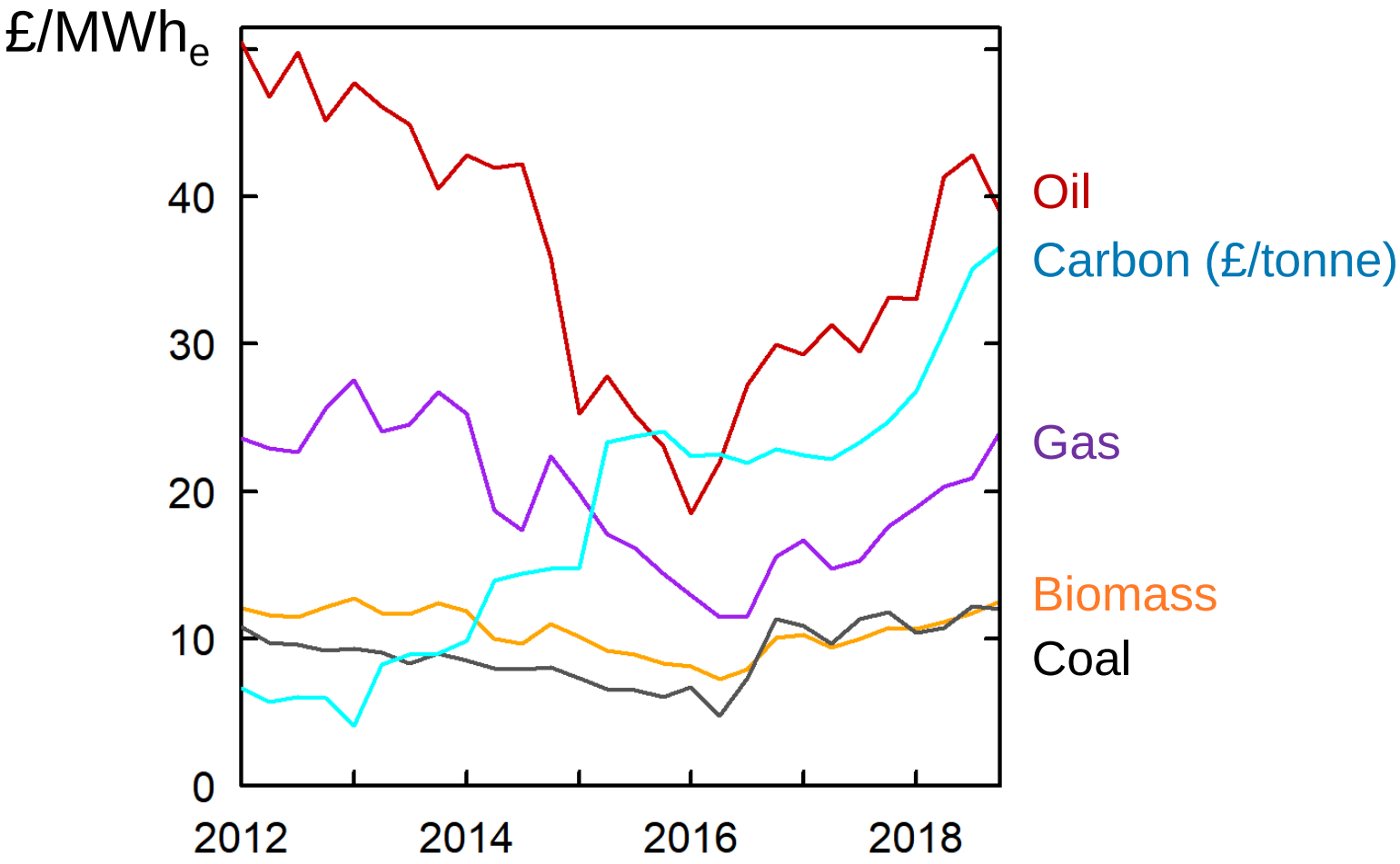


Source — Ward, 2019, Energy Policy

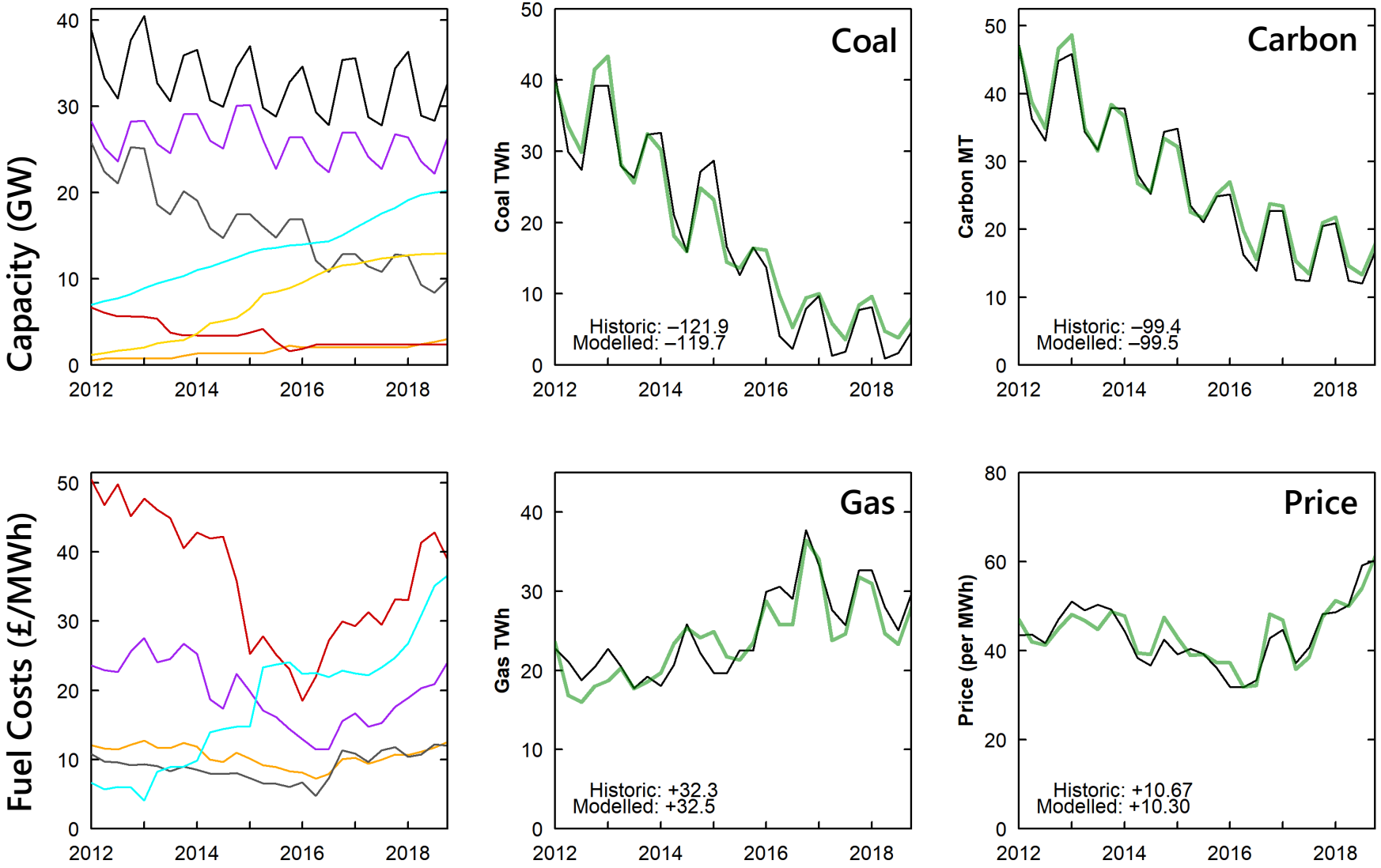
Model inputs: demand & capacity



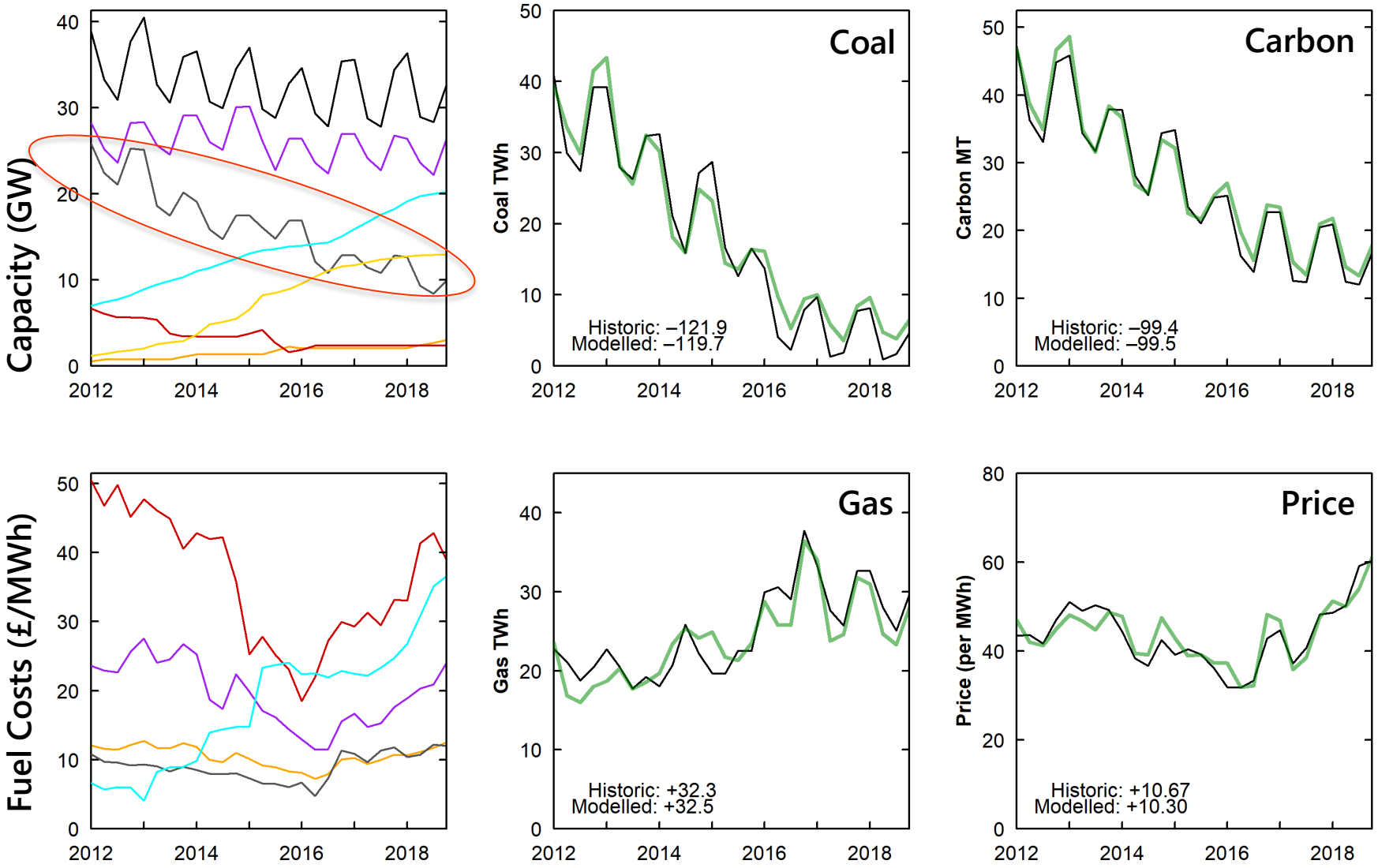
Model inputs: fuel & carbon prices



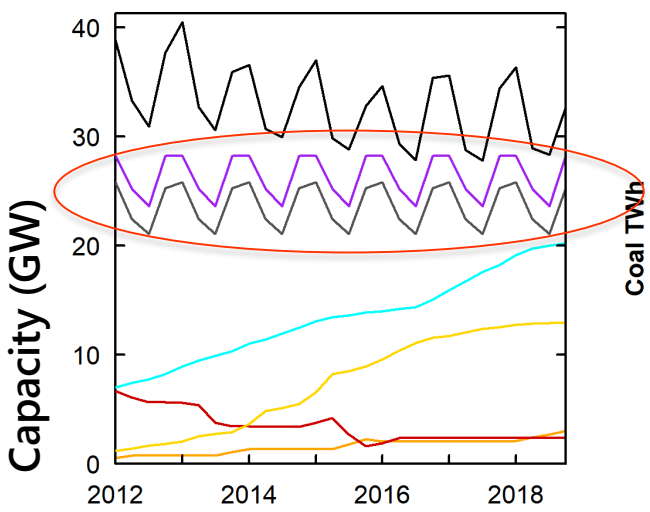
What if... nothing was fixed?

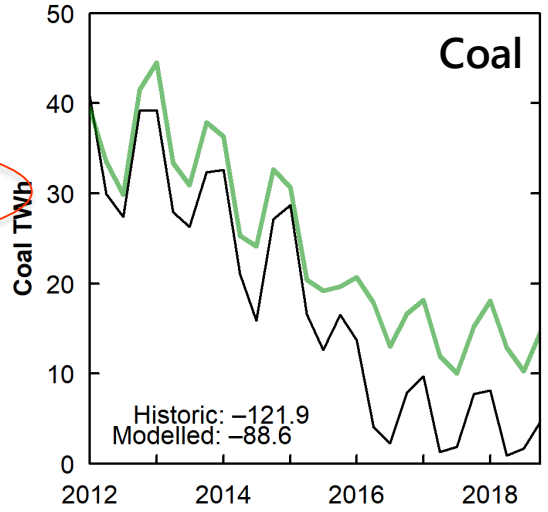


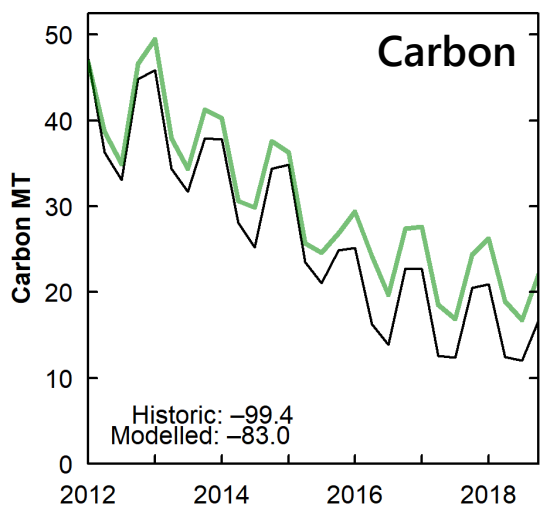
What if... fossil capacity was fixed?

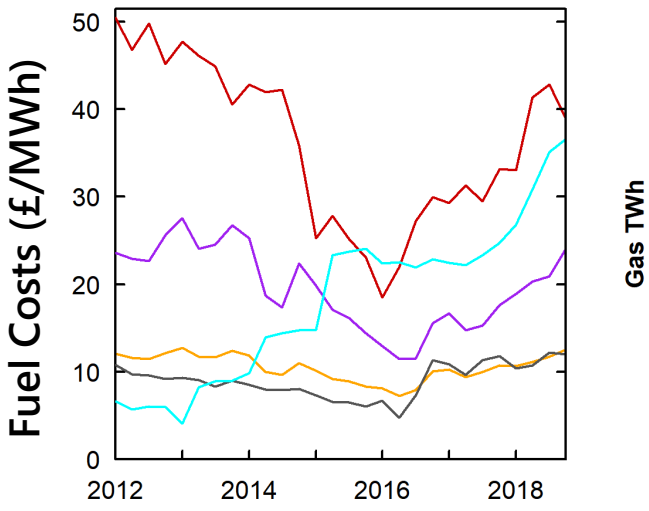


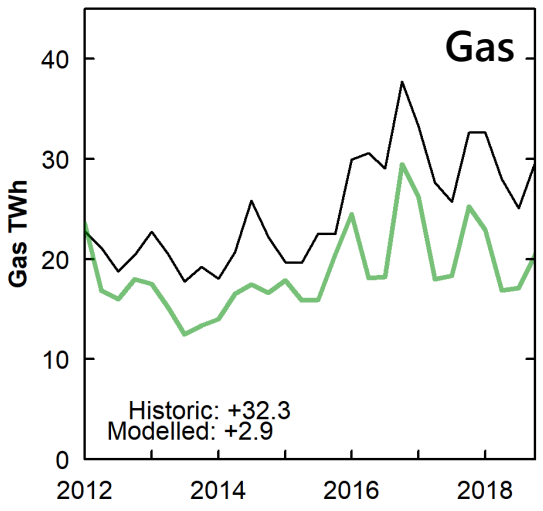
What if... fossil capacity was fixed?

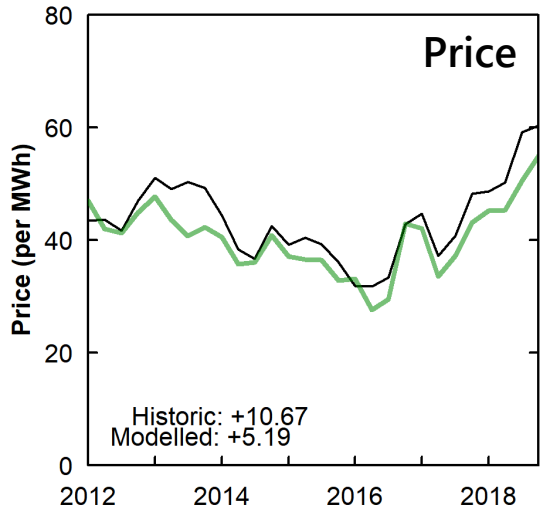




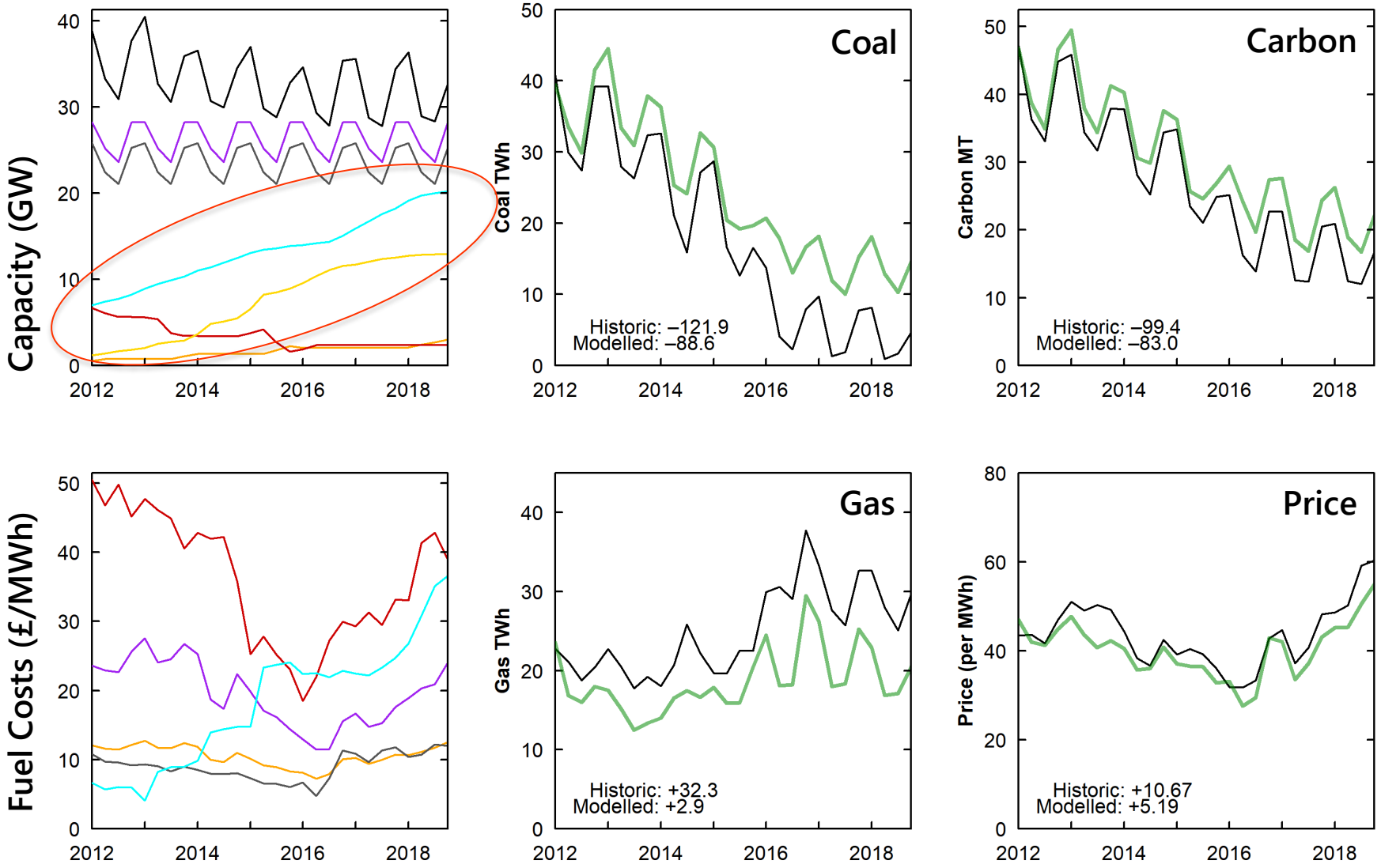




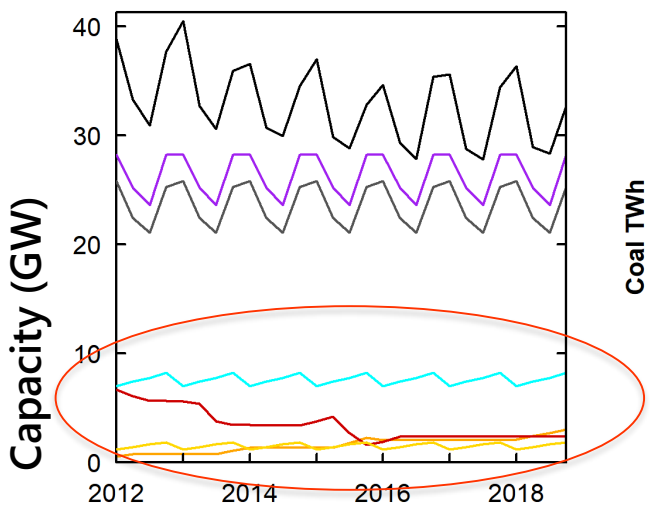


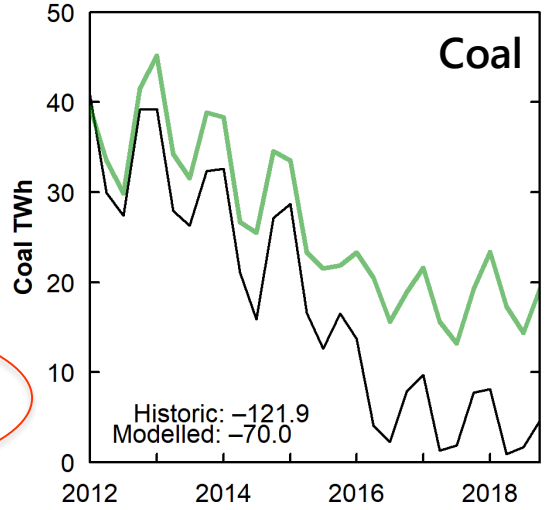


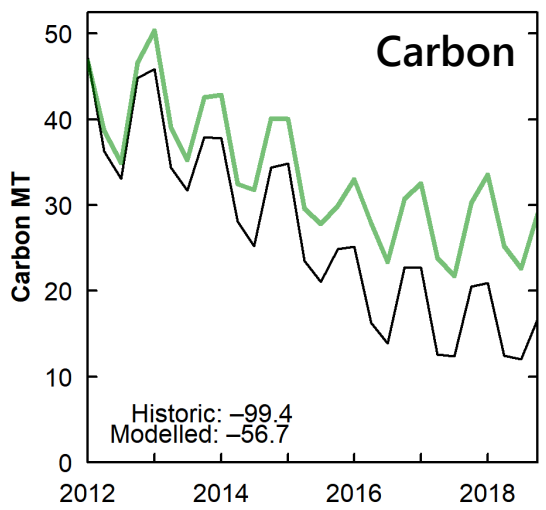
What if... fossil & renewable capacity was fixed?

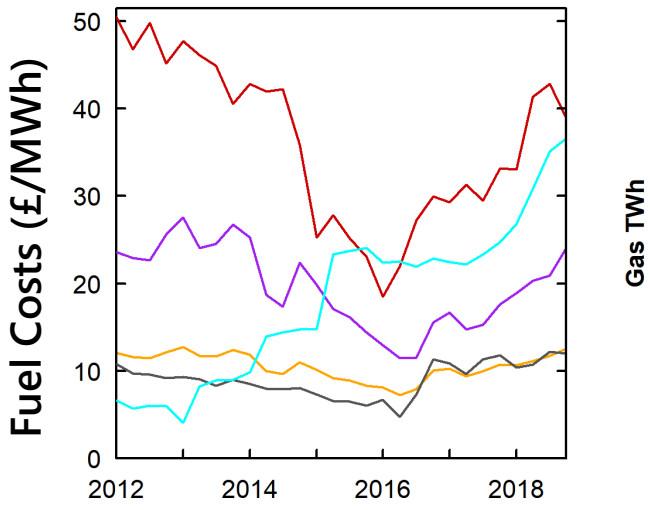


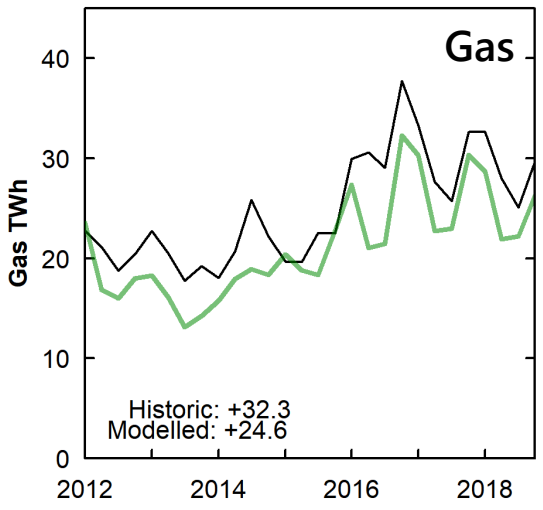
What if... fossil & renewable capacity was fixed?

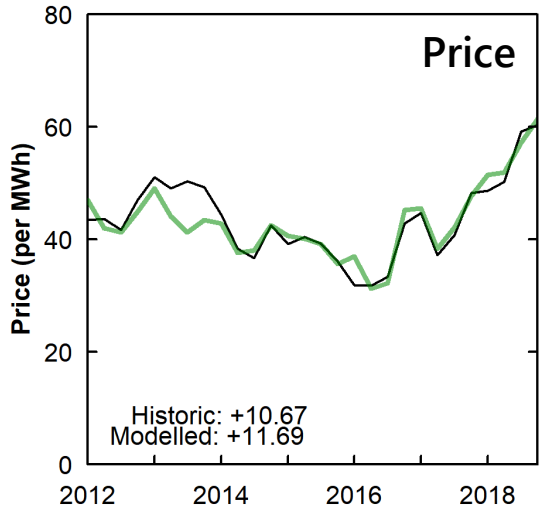




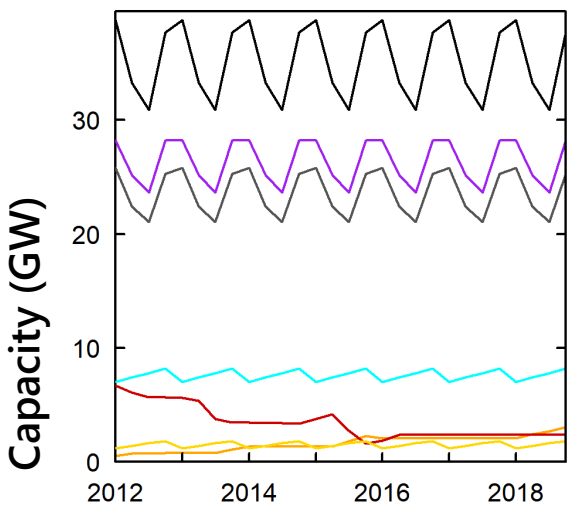


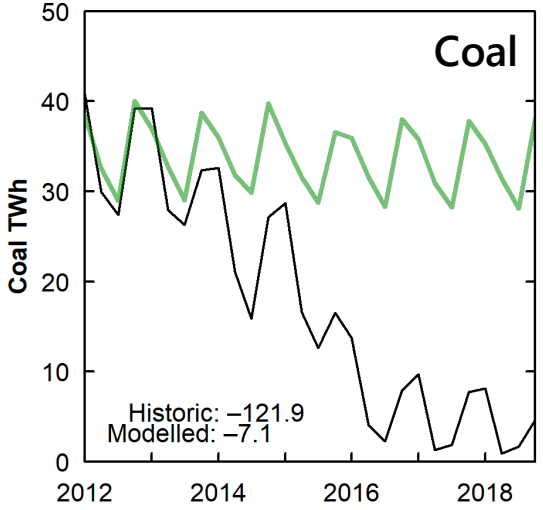


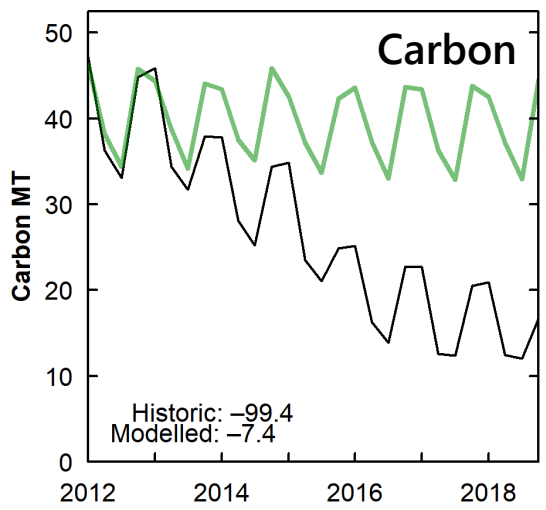


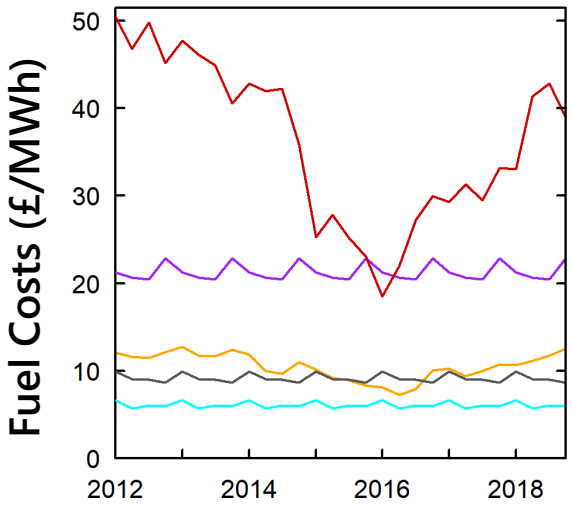


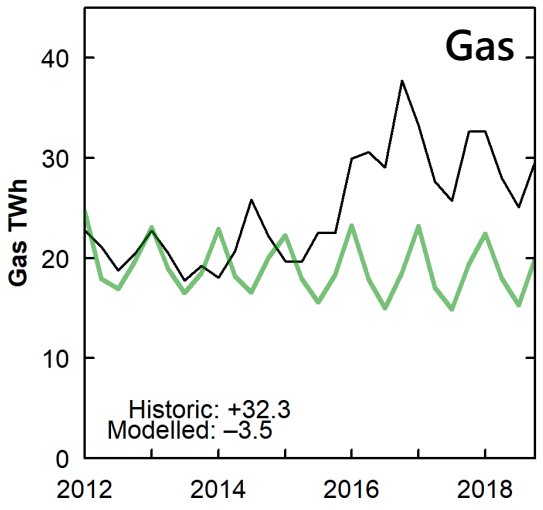
What if... everything was fixed?

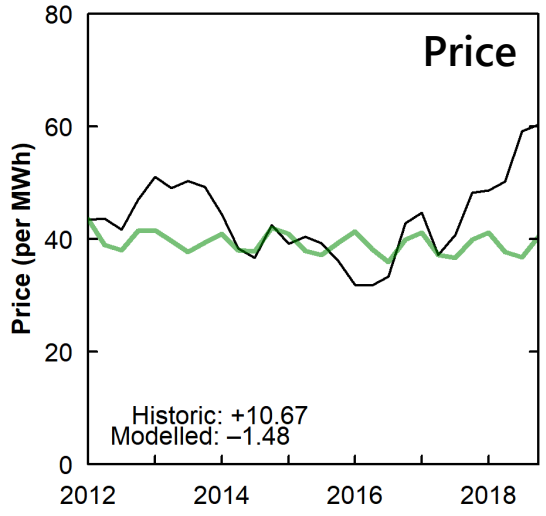












What drove down emissions?

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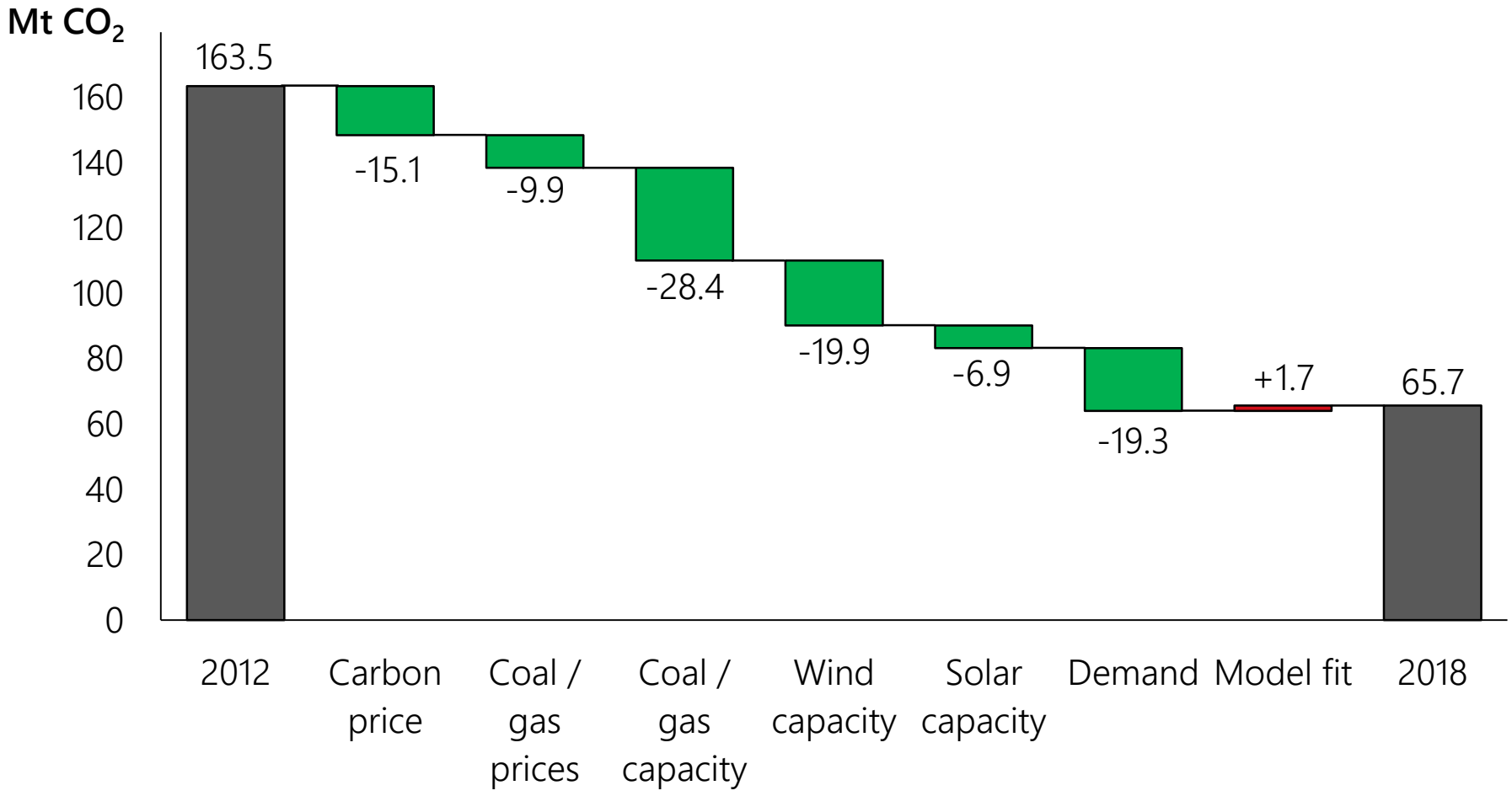

What drove up prices?

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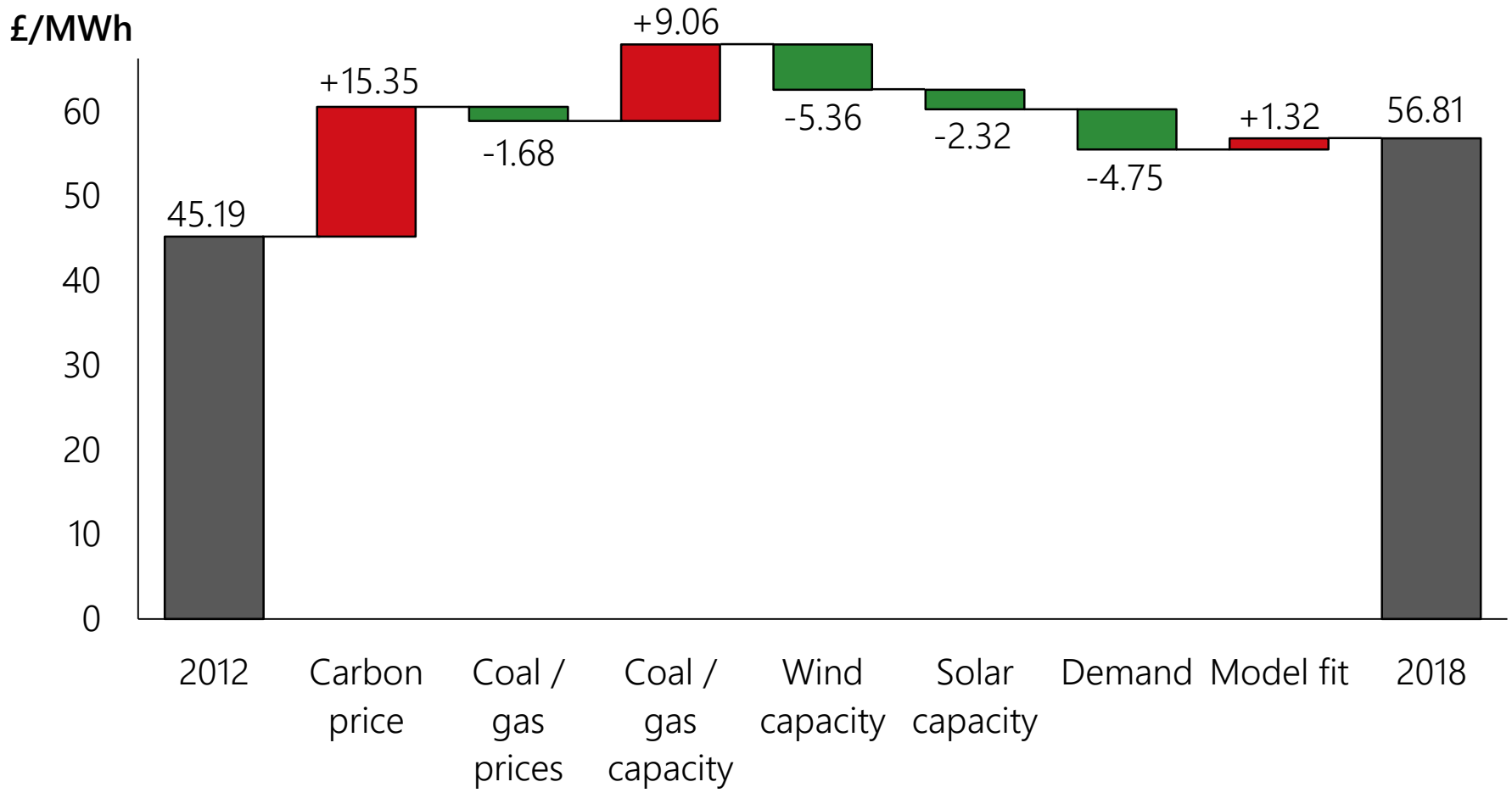

The “non-marginal” impacts

	Impact from 2012 to 2018	
	Emissions (g/kWh = t/GWh)	Money (£/MWh = £m/TWh)
Wind	–582	–£46
Solar	–668	–£66
Demand	+750	+£54

Renewable support schemes

- Renewables Obligation Certificates
  - "Tradable green certificates", technology-differentiated, from 2003-c.2015
- Feed-in Tariffs
  - Small-scale generators, from 2010
- Contracts for Difference
  - Large generators, auctioned contracts, from 2015
    - First schemes at "administered prices"

Impact on consumer prices

- Wind subsidy of £85/MWh (of wind output)
- Merit Order Effect of £5.36/MWh (market-wide)
- Overall impact: increase of £4.60/MWh (market-wide)

- Solar subsidy of £80/MWh (of PV output)
- Merit Order Effect of £2.32/MWh (market-wide)
- Overall impact: increase of £0.50/MWh (market-wide)

The cost of saving carbon

- Cost of renewable subsidies versus estimated savings:

- Wind saved 20 m tonnes CO_2 for £147/tonne
- PV saved 7 m tonnes CO_2 for £120/tonne
- Carbon prices saved 15 m tonnes CO_2 for £14/tonne

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Thank you

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