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Imperial means Intelligent Business

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

Richard Green, Iain Staffell and Kate Ward

2 October 2019 – work in progress!

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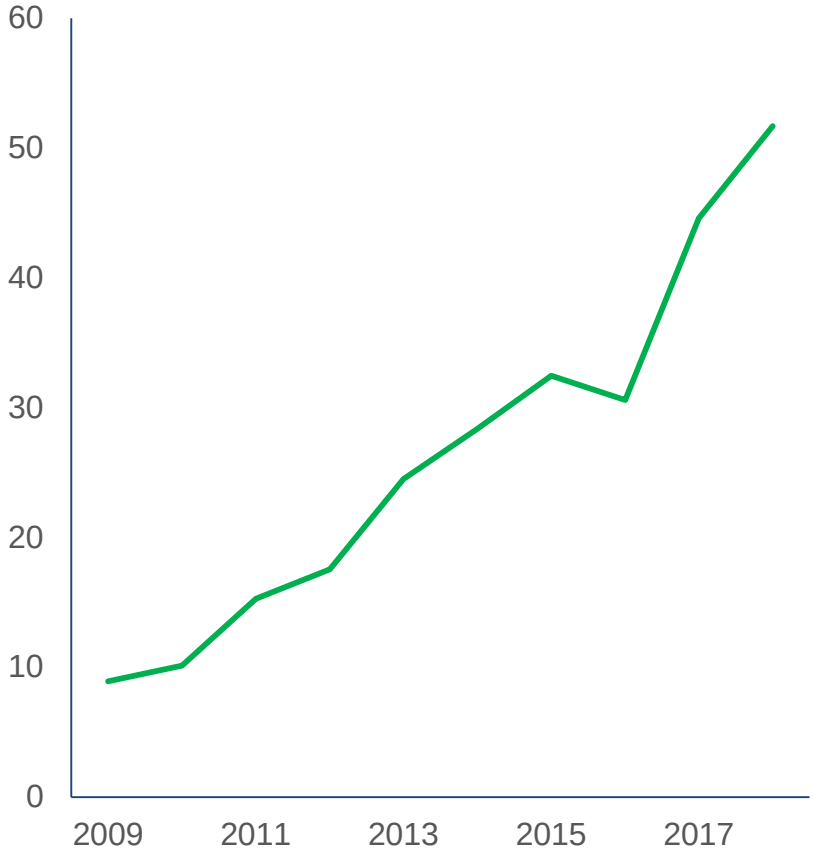
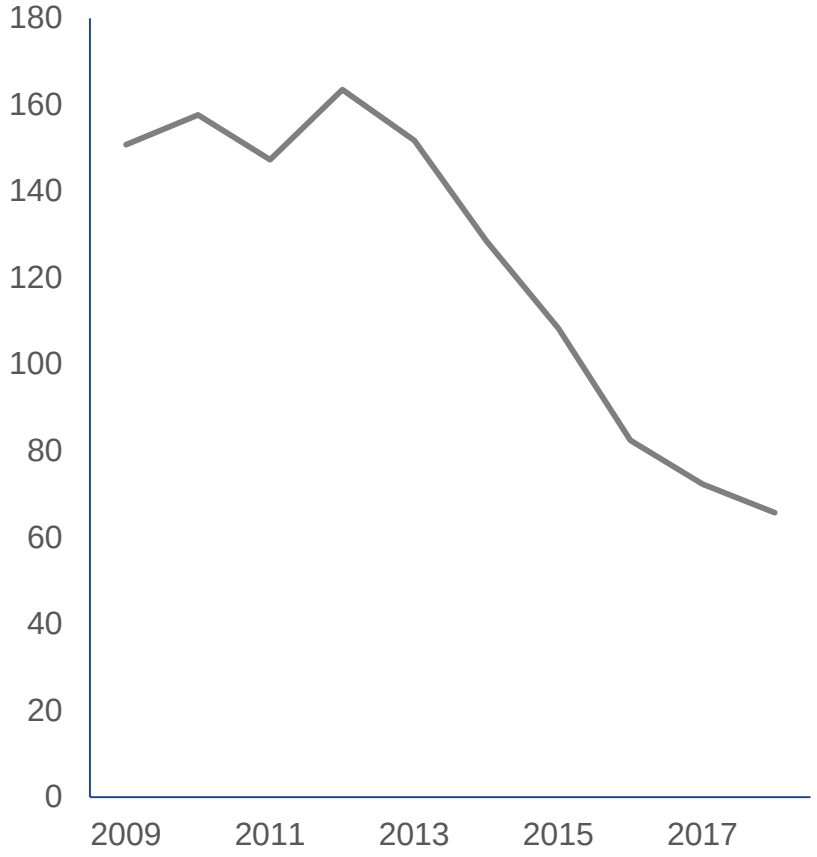
Some recent British data

Problem solved?

Wind Generation (TWh)



CO_2 Emissions (m. Tonnes)



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Some recent British data

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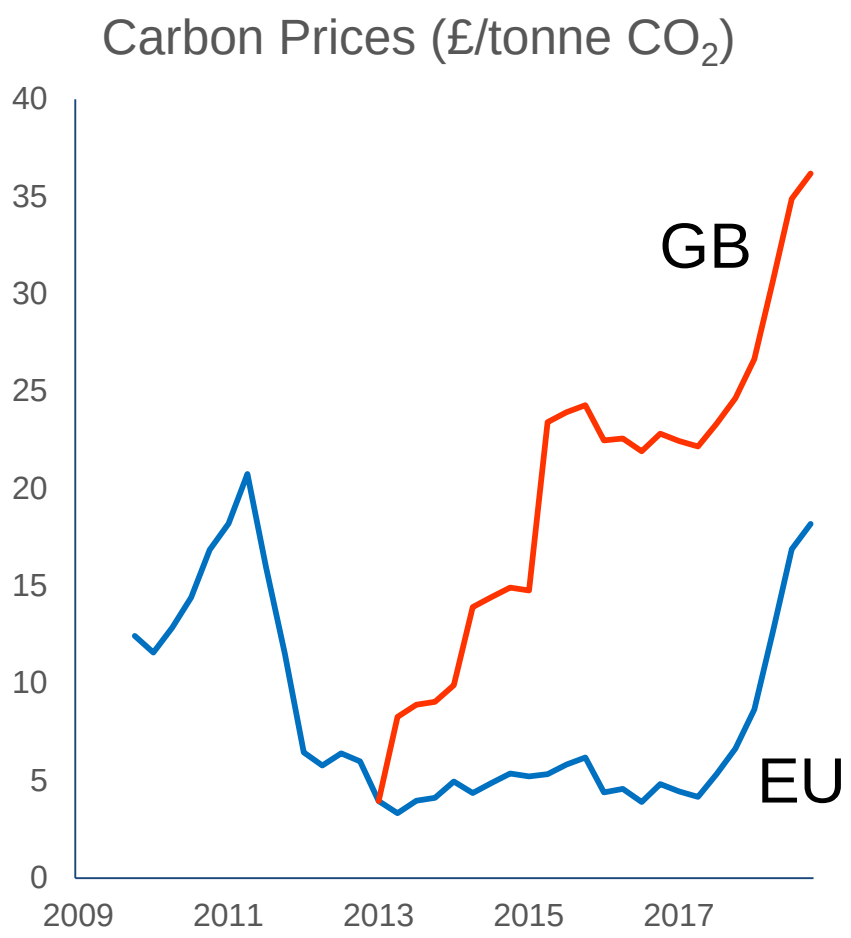

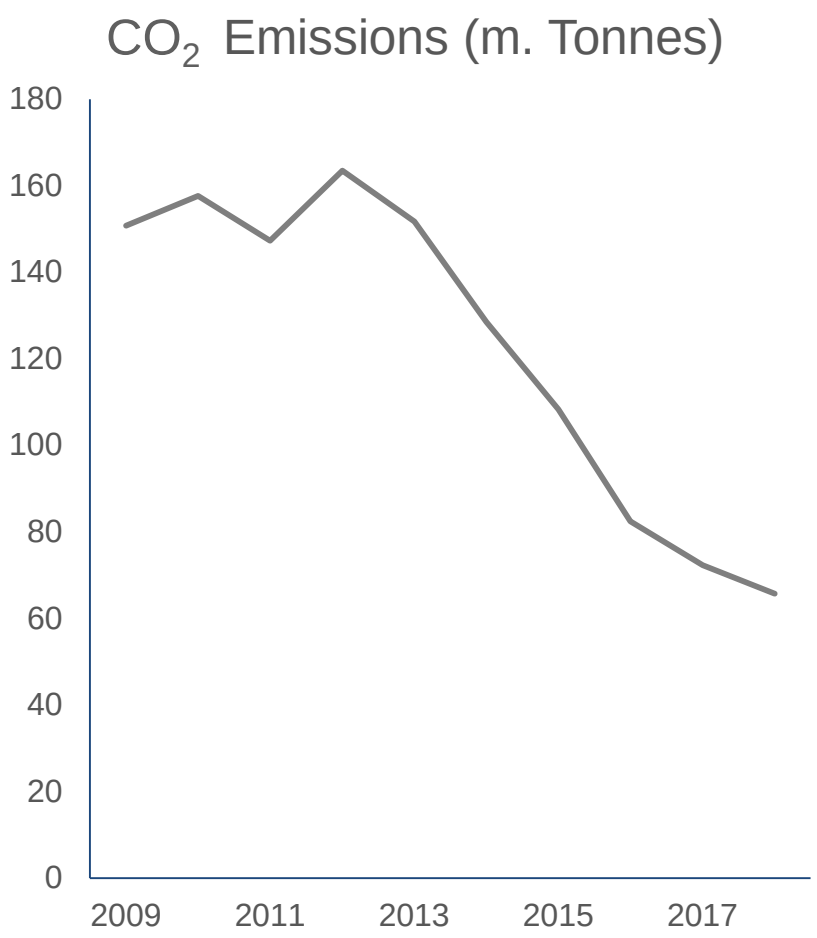

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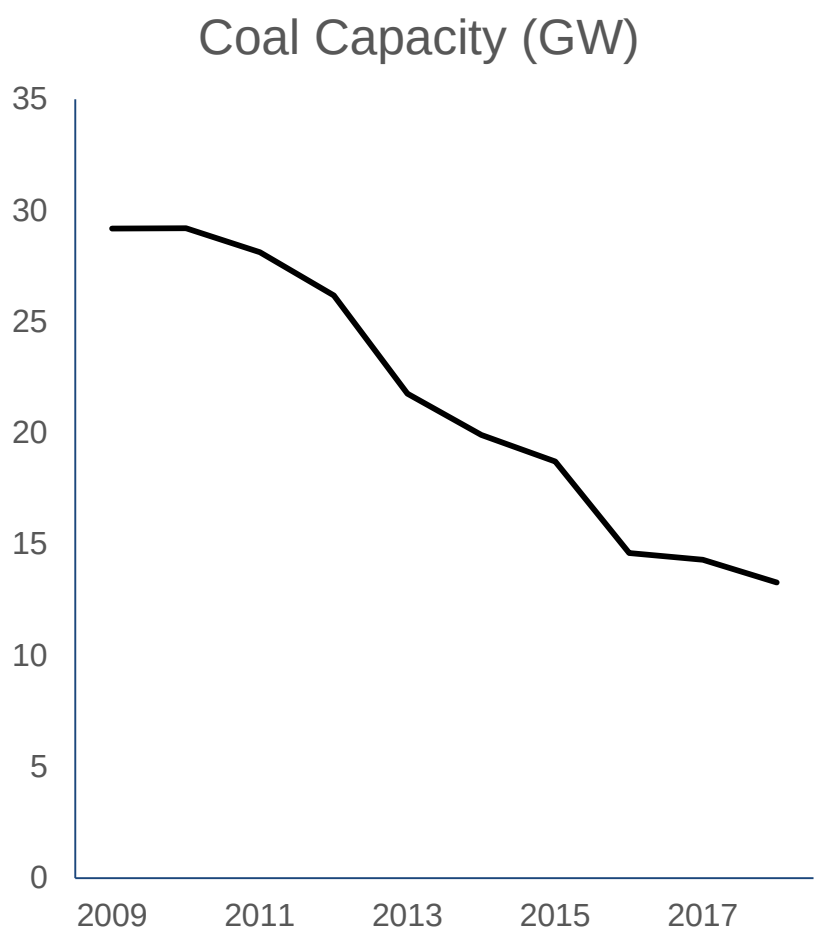

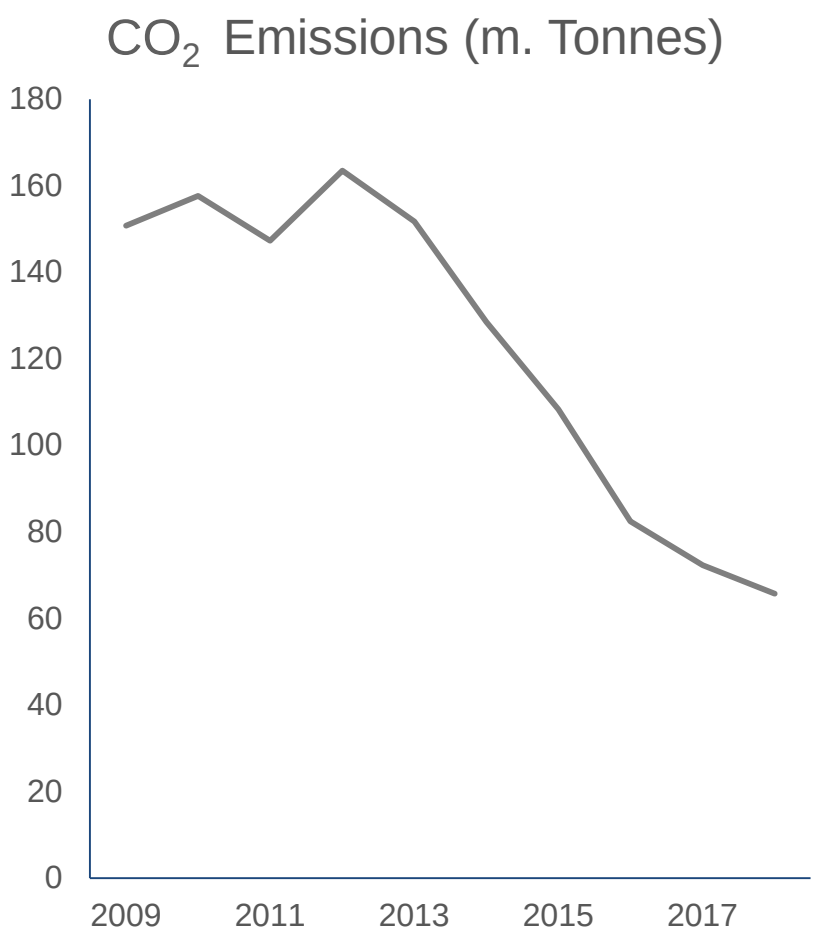

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Agenda

- How generation changed in Britain
- 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?

How did generation change?

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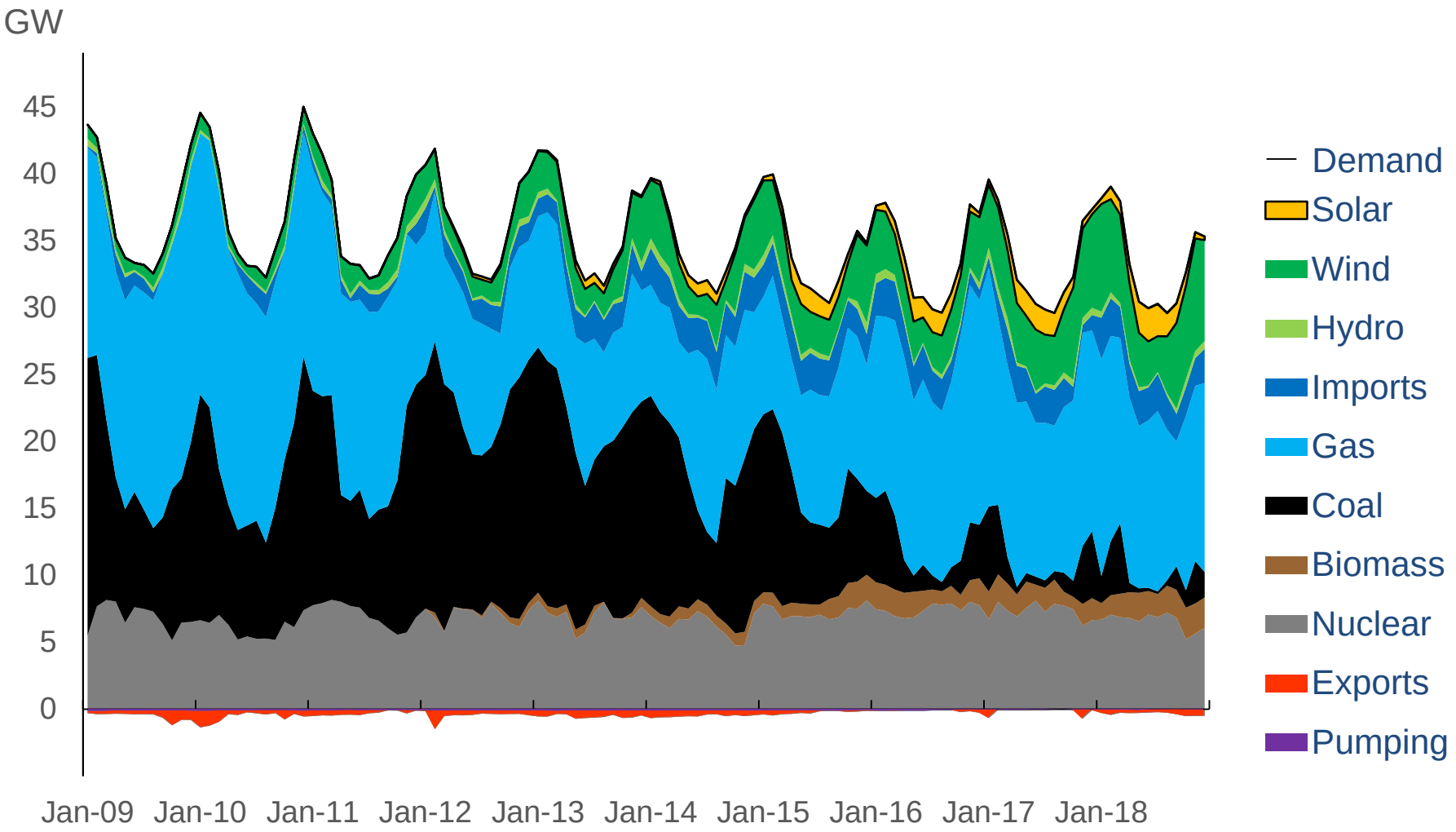
Generation in Great Britain

Monthly averages



The power of carbon prices

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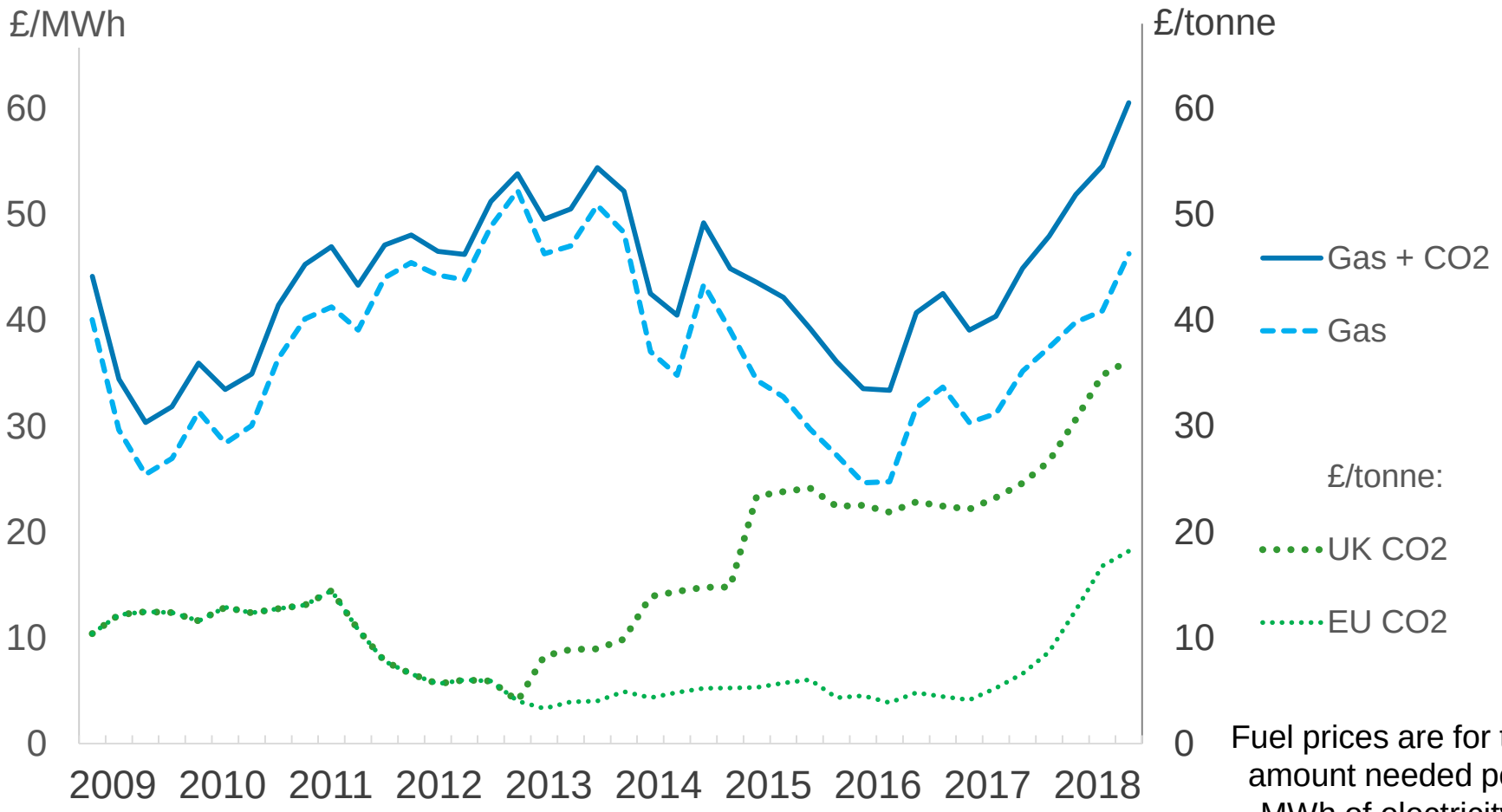
GB Fuel & Electricity Prices

Contracts for delivery at different times



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

Sources: Elexon, BEIS and ICE

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GB Fuel & Electricity Prices

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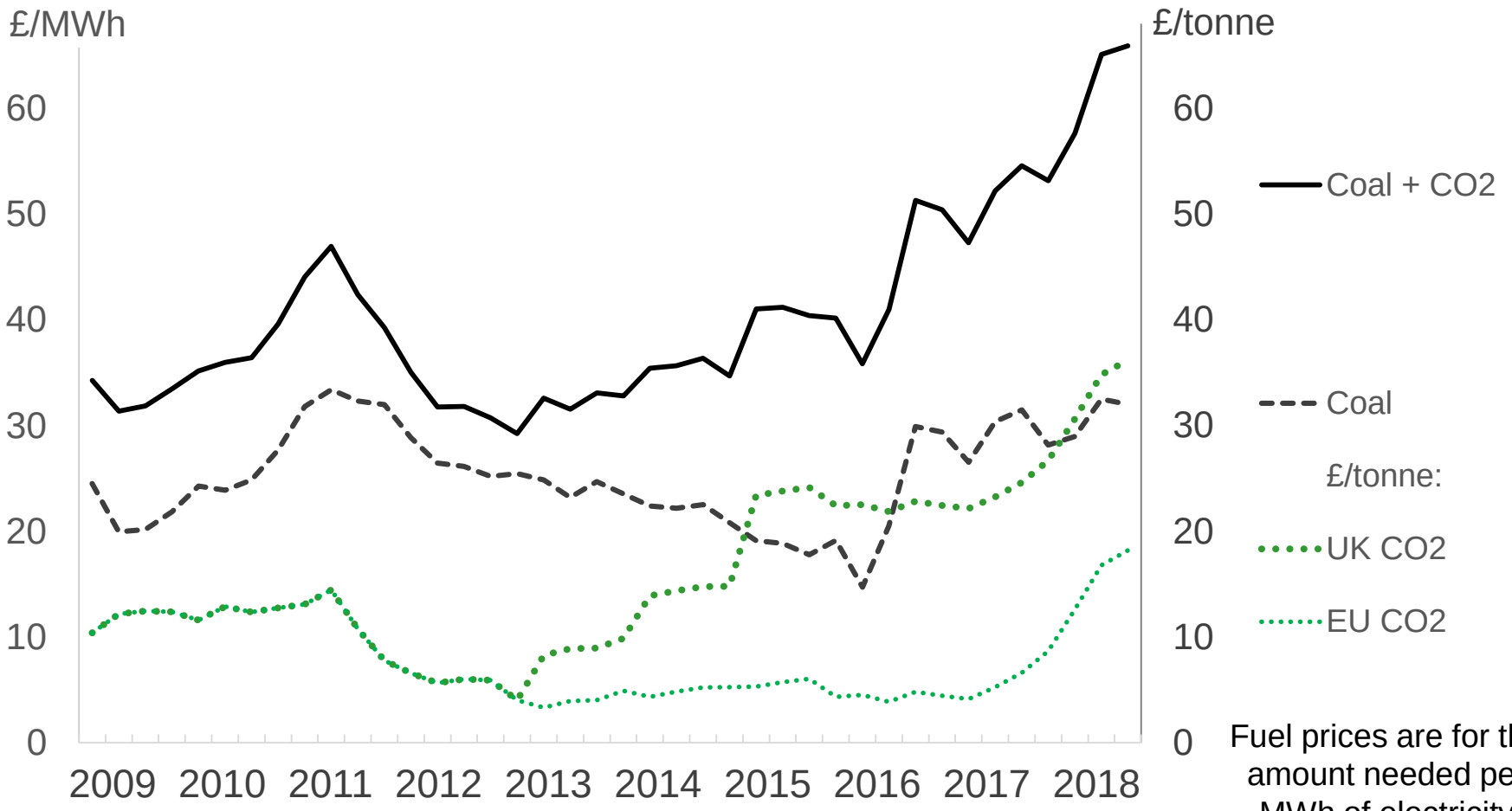

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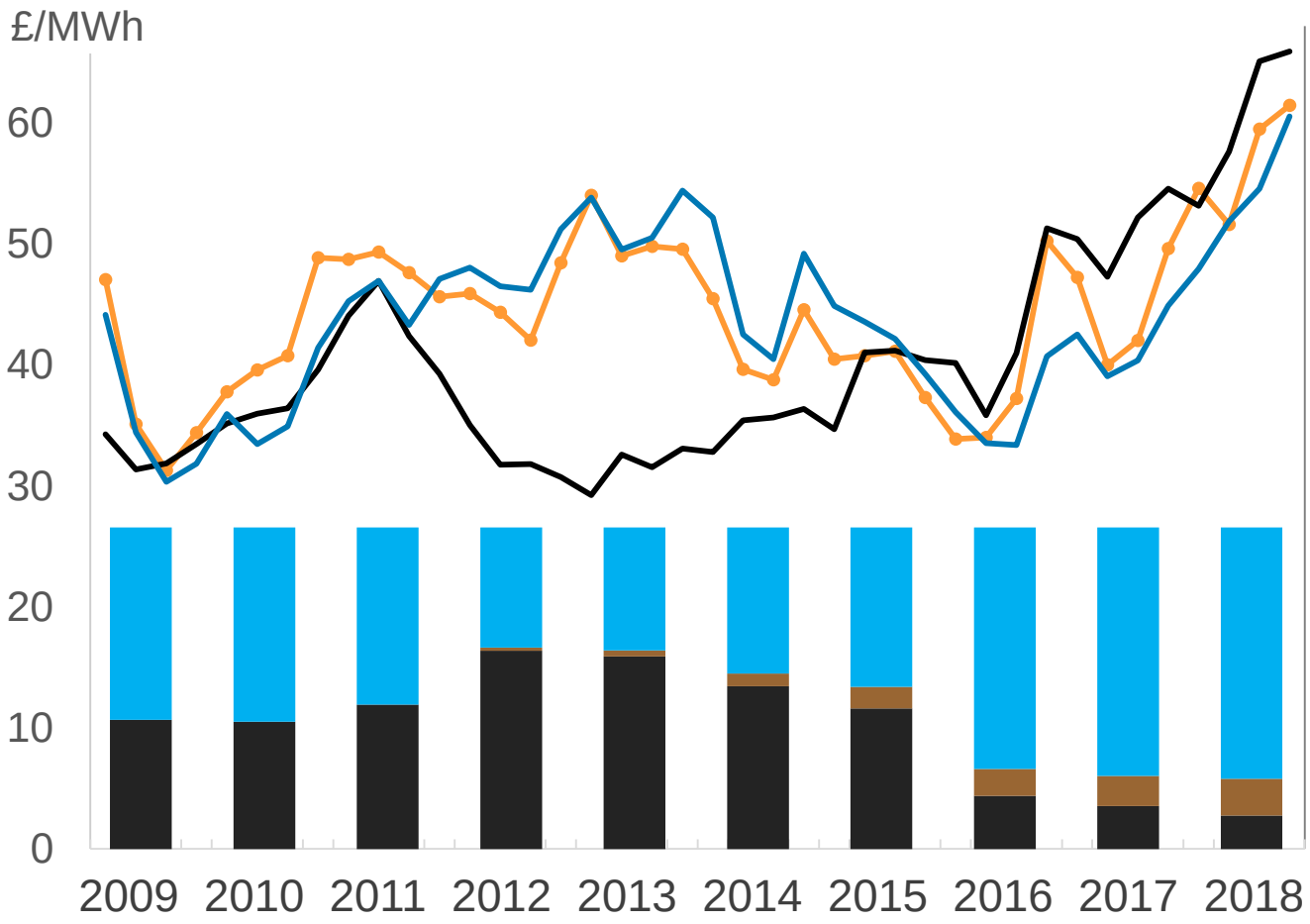

Share of thermal output:

- Gas
- Biomass
- Coal

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

Sources: Elexon, BEIS and ICE

Previous studies

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Marginal CO_2 Emissions

Econometric studies

Who?	Where?	What?	How Much?	Reference
Hawkes	Great Britain	Demand	690 kg/MWh	*Energy Policy*, 2010
Siler-Evans *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

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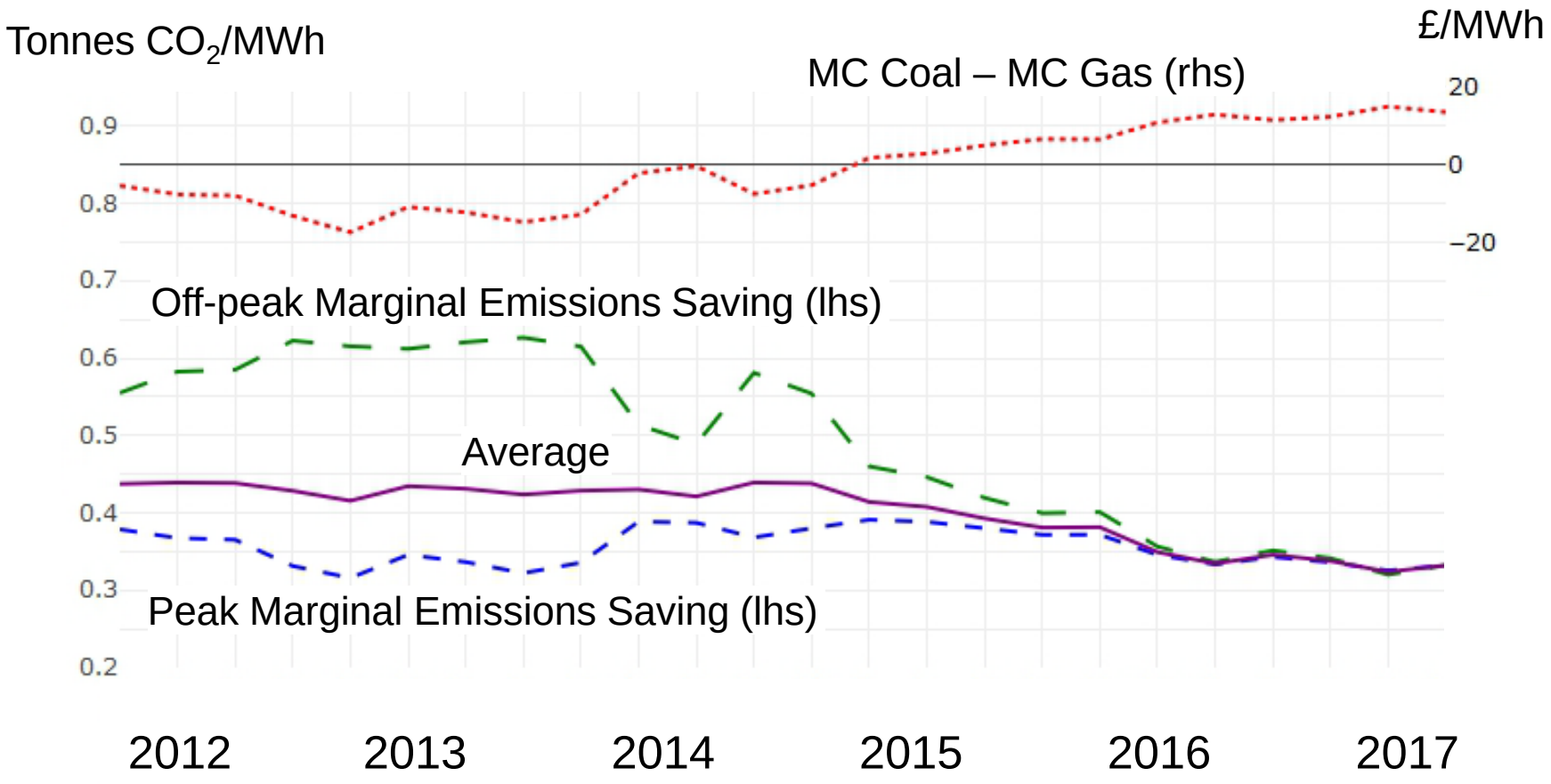
Emissions savings from wind

Chyong, Guo and Newbery (*EPRG WP*, 2019)



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Renewables and Prices

- The Merit Order Effect
  - Renewable output depresses prices until capacity adjusts
  - Sensfuß *et al.* (*En. Pol.*, 2008)
  - Sáenz de Miera *et al.* (*En. Pol.*, 2008)
- The Twomey-Neuhoff Effect
  - Renewable output depresses its own price
  - Twomey and Neuhoff (*En. Pol.*, 2010)
- The race between costs and revenues
  - Capacity gives learning, cutting costs; but revenues fall too!
  - Green and Léautier (*Toulouse WP*, 2015)

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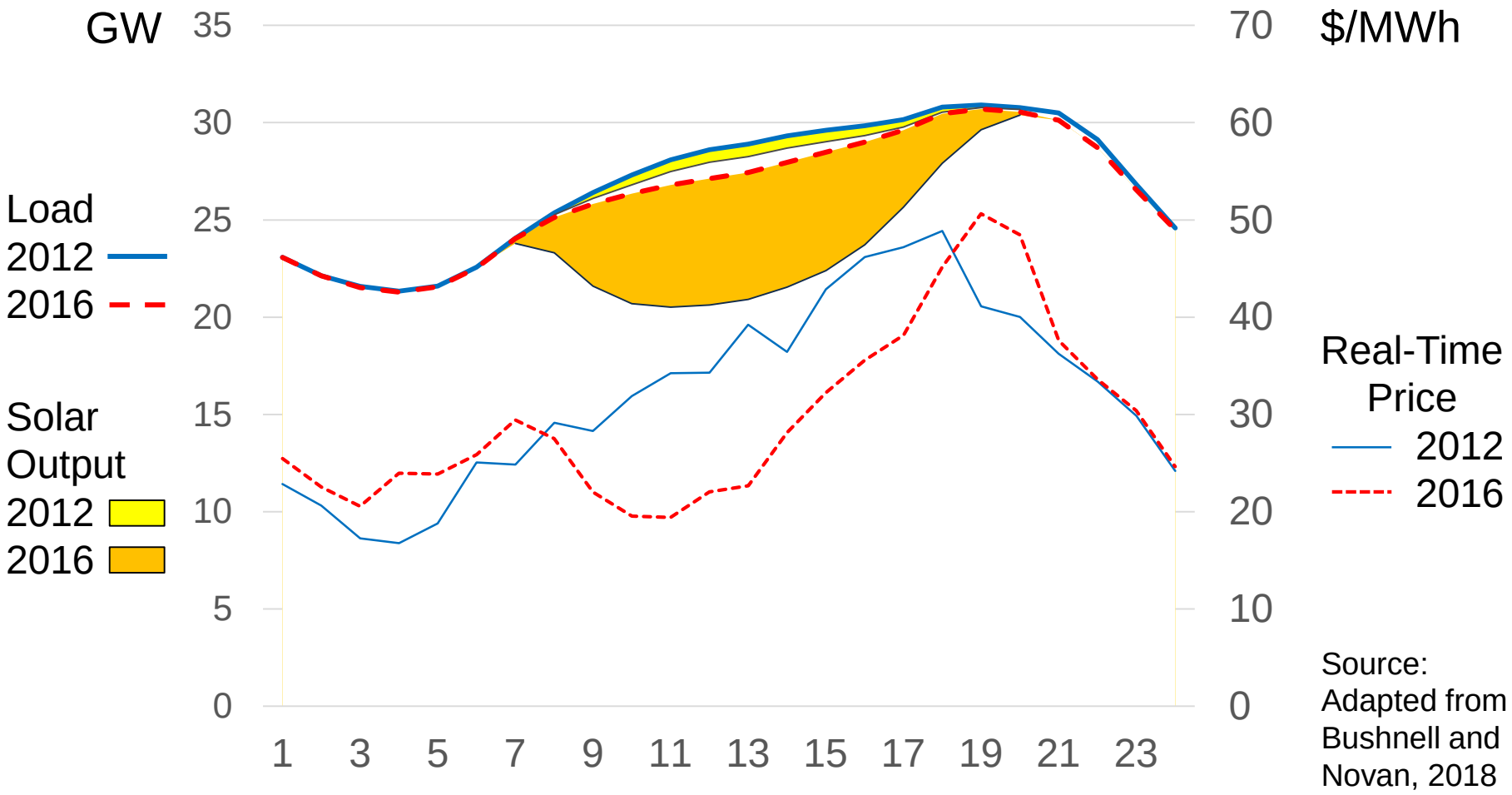
Load, PV Output and Prices

California, 2012 and 2016



Source: Adapted from Bushnell and Novan, 2018

See also Hirth (2015) http://dx.doi.org/10.1049/iet-rpg.2014.0101

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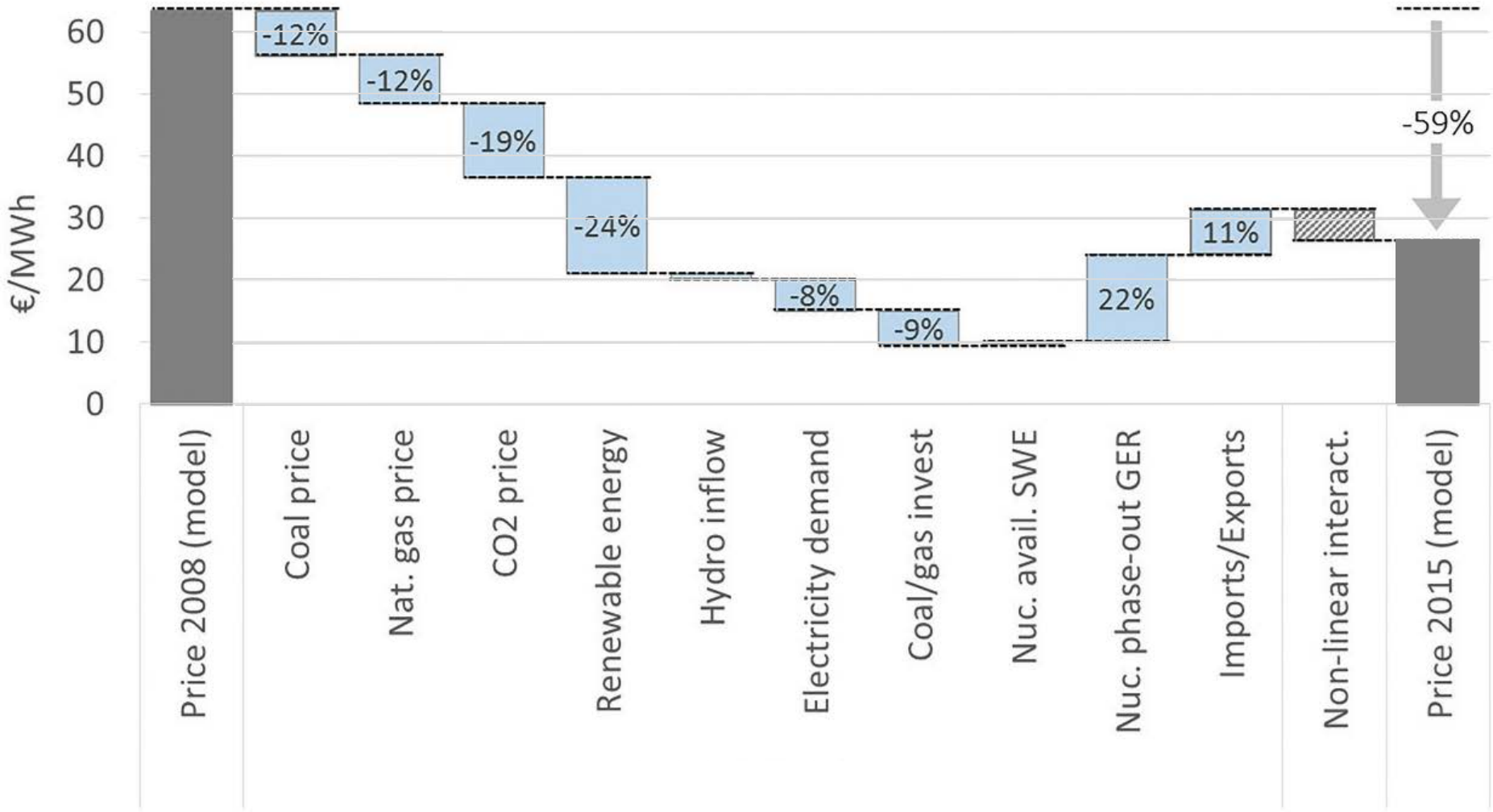
German Electricity Prices

Decomposition by Hirth (*En Jnl*, 2017)



The Shapley Value

Getting rid of the residual

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The Shapley Value

A concept from cooperative games

- 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

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

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The Shapley Value of Wind

Applying the concept to our setting

- Worth is carbon emissions, which fell from 164 to 66 mt.
- Carbon price rose from £6/tonne to £32/tonne
- Coal price rose from £9/MWh to £10/MWh and gas price fell from £21/MWh to £19/MWh
- Coal capacity fell from 26 GW to 14 GW and gas capacity fell from 31 GW to 29 GW
- Wind capacity rose from 7 GW to 22 GW
- Solar PV capacity rose from 1 GW to 13 GW
- Demand fell from 319 TWh to 294 TWh

Simulation modelling: Enhanced Merit Order Stack

Ward, Green & Staffell (*En. Pol.* 2019)

https://doi.org/10.1016/j.enpol.2019.01.077

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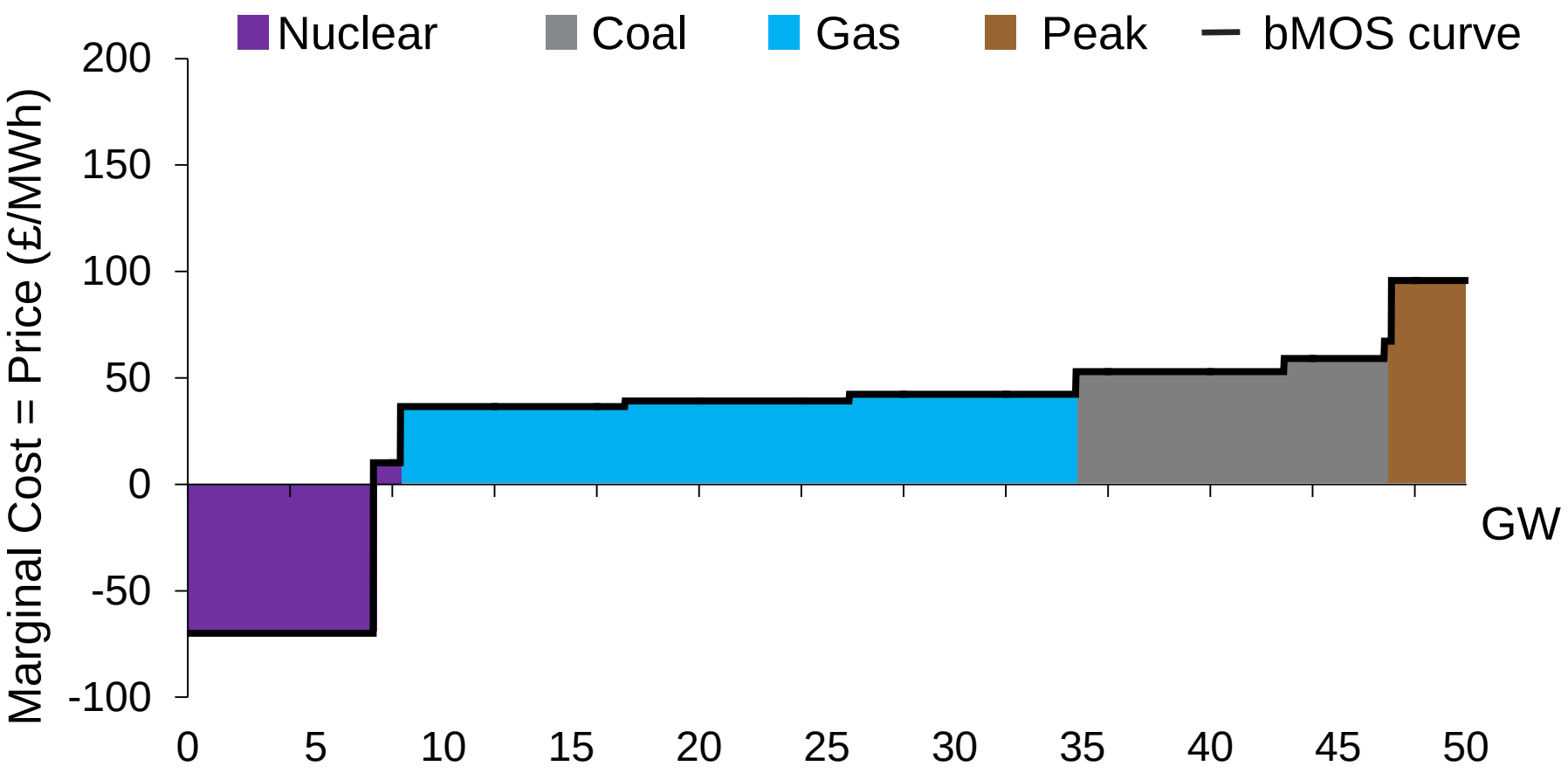
Merit Order Stack

Typical stack model with blocks of plant



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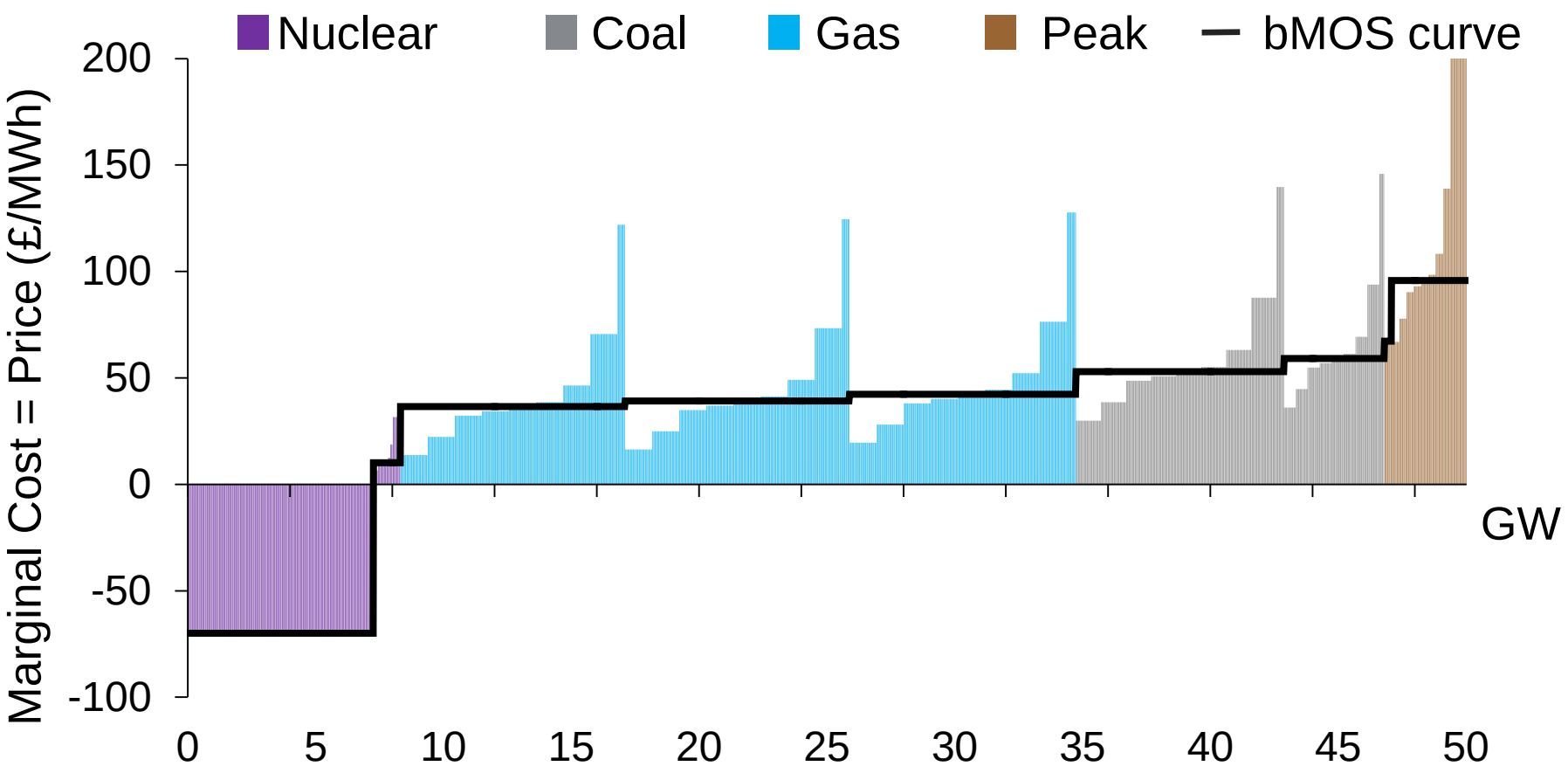
Merit Order Stack

Each plant type has tranches with different bids



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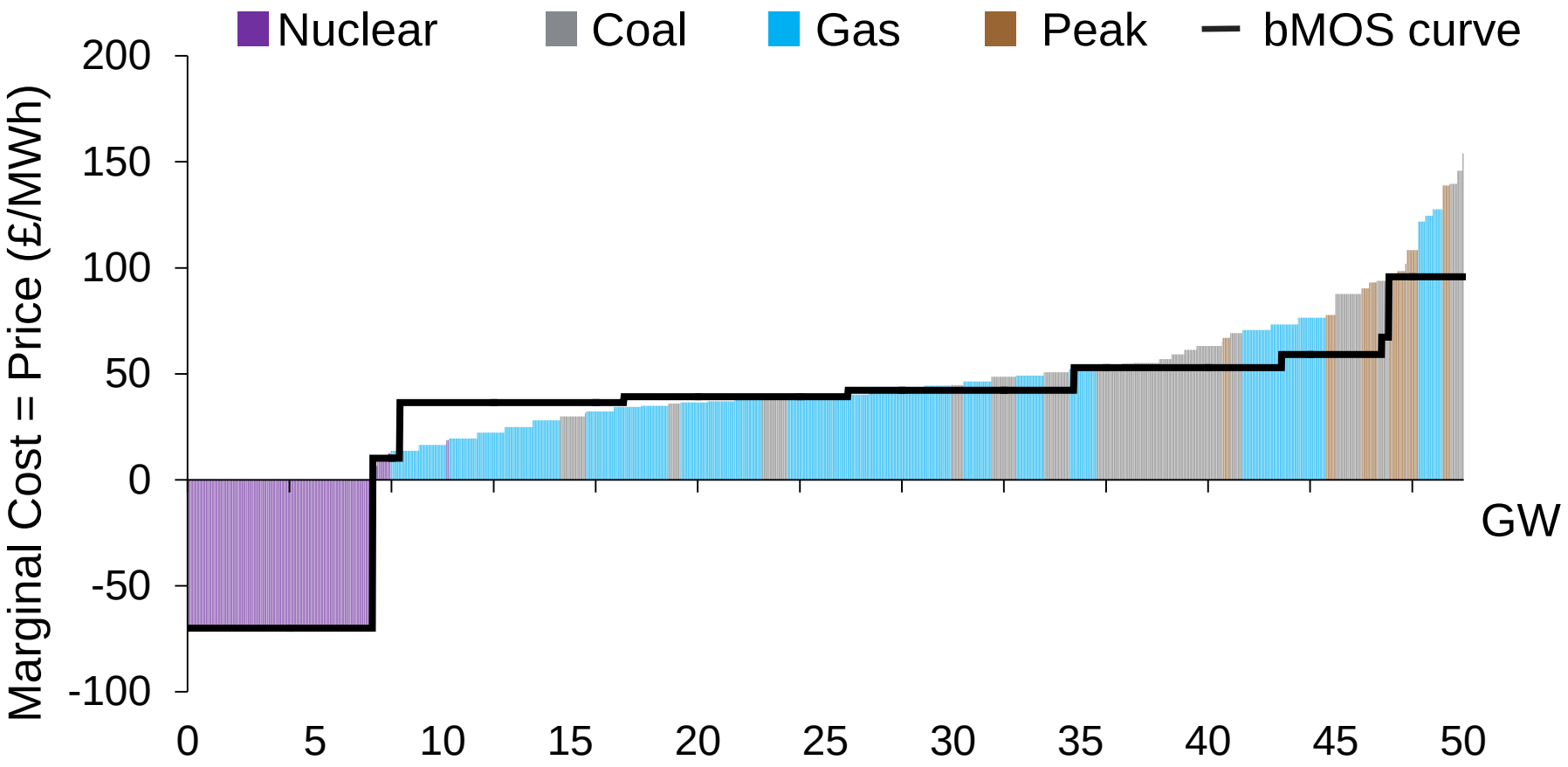
Enhanced Merit Order Stack

Tranches rearranged: part-loading in the merit order



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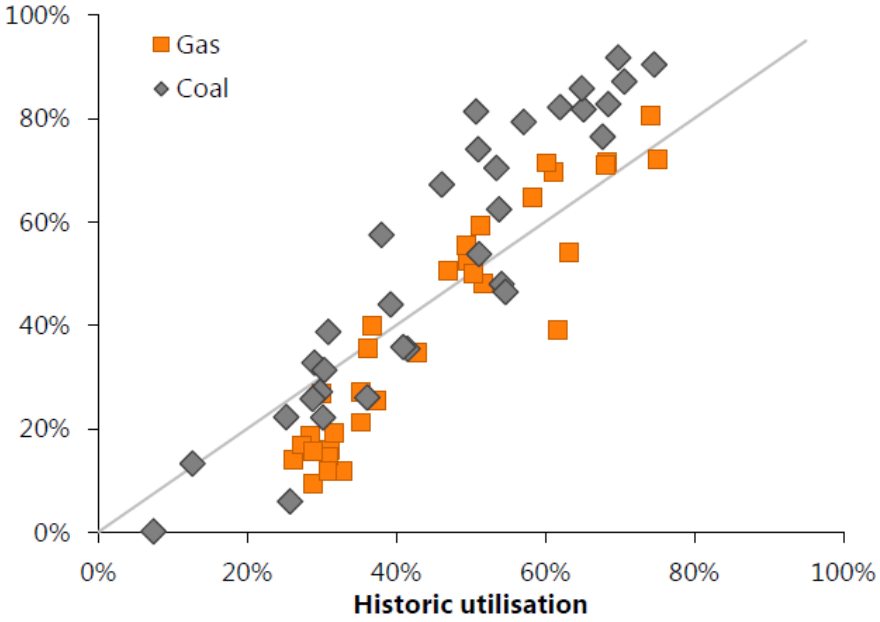
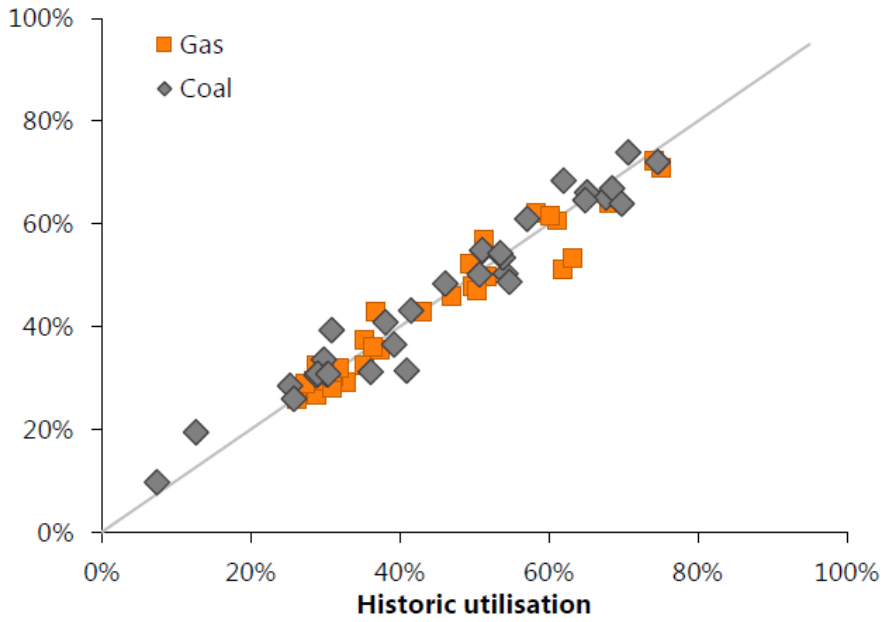
Standard (left) versus Enhanced Merit Order Stack

Plant Utilisation (load factor)





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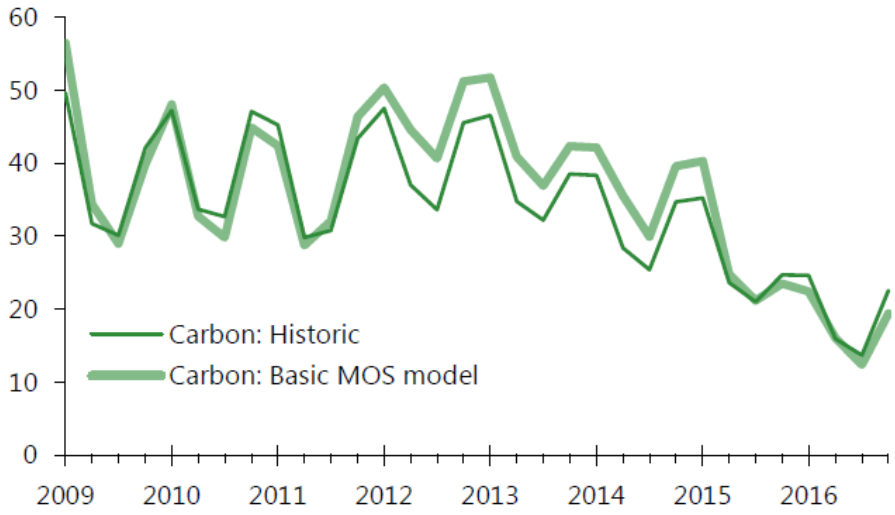
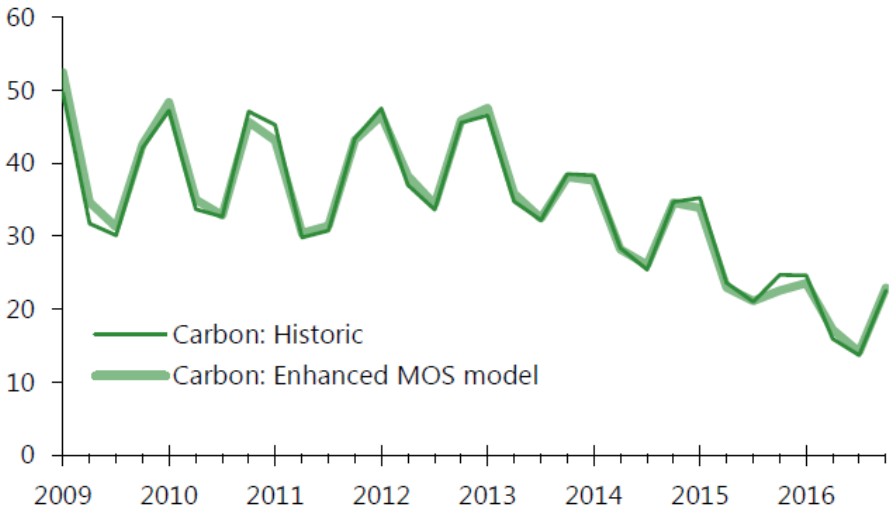
Standard (left) versus Enhanced Merit Order Stack

CO_2 emissions (m. tonnes)





Simulation results

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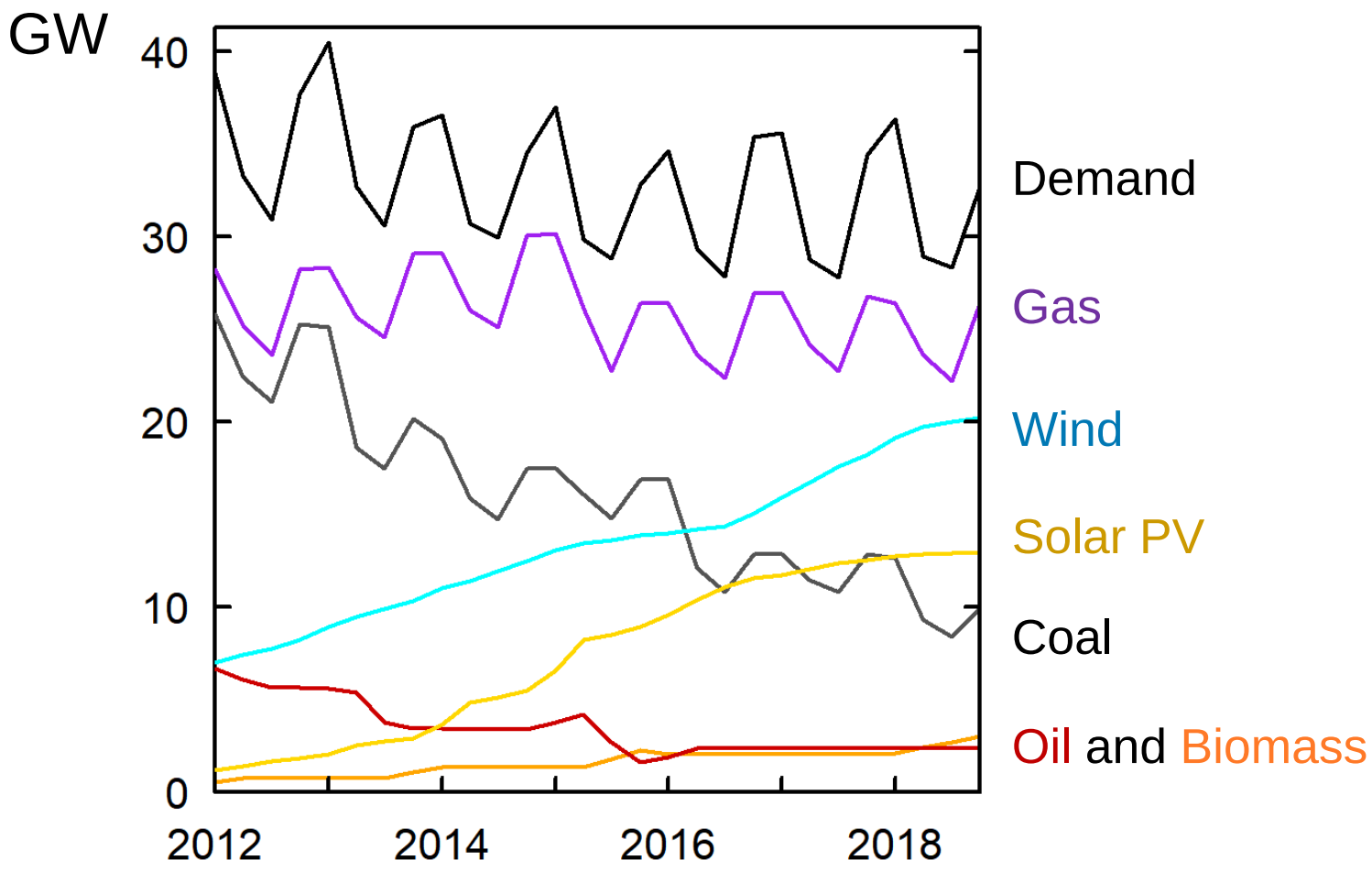
Model inputs

Demand and available capacity



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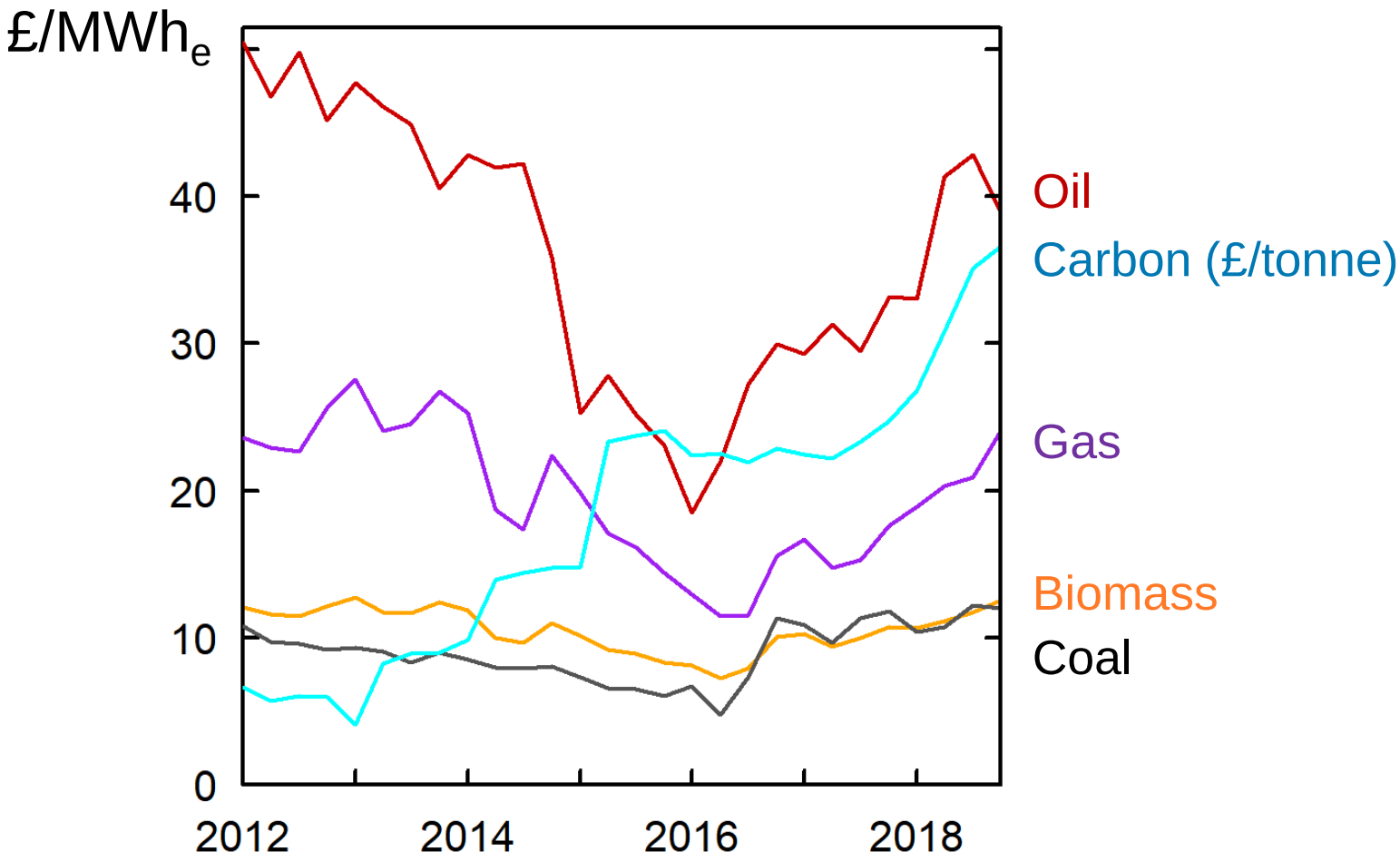
Model inputs

Fuel and carbon prices



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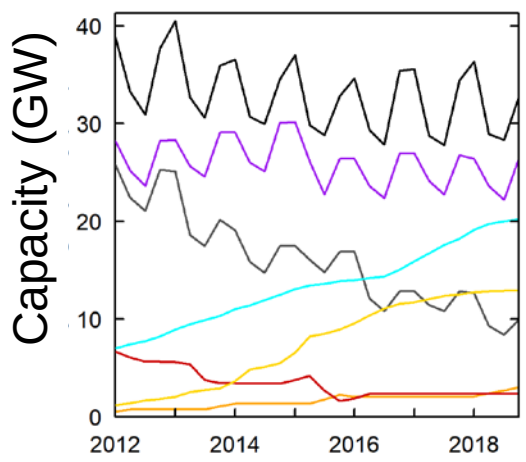
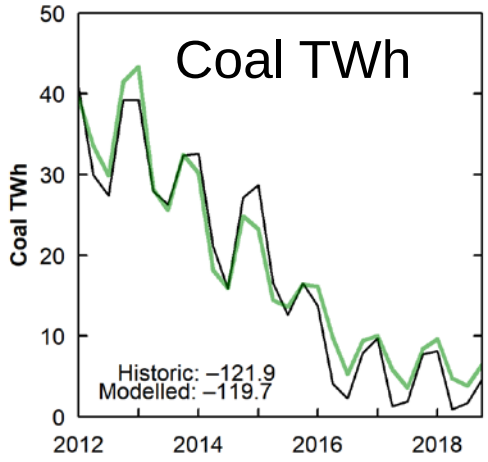
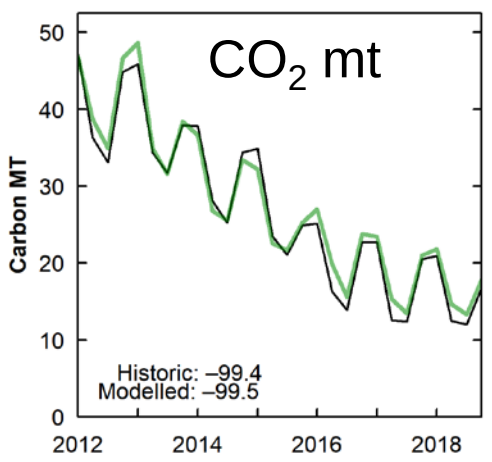
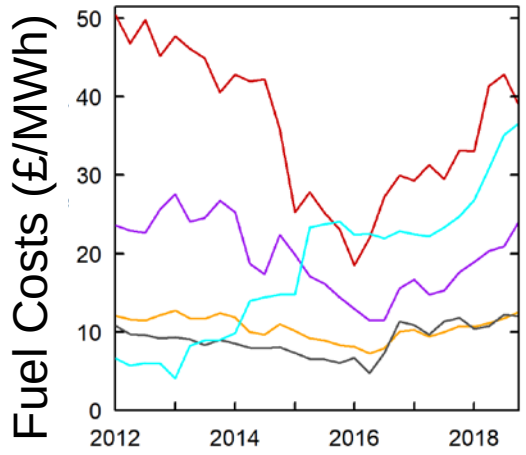
Model inputs and outputs

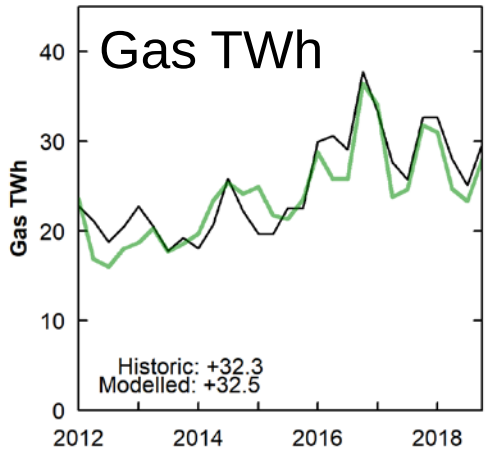
Black = actual; Green = simulation

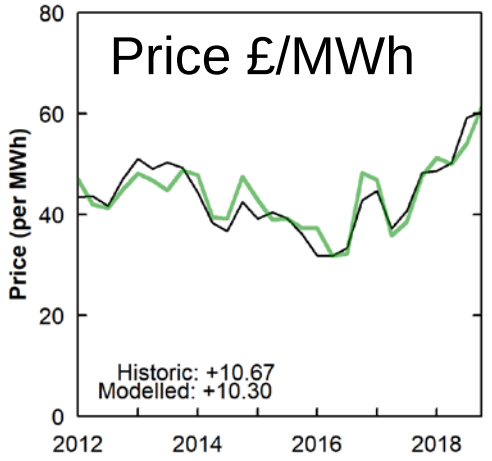












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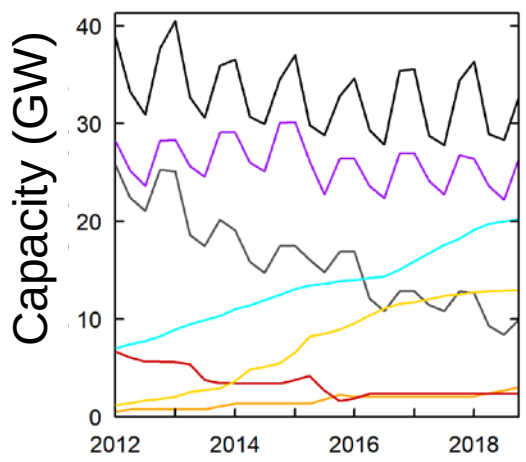
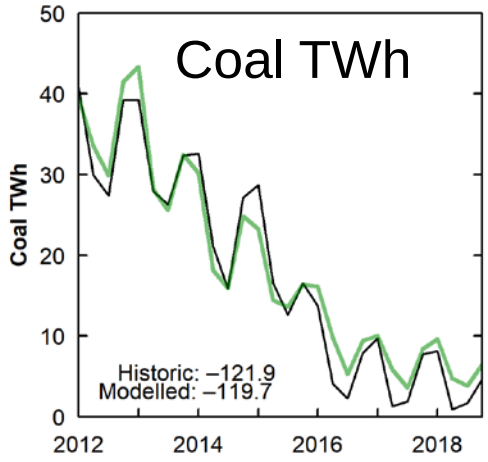
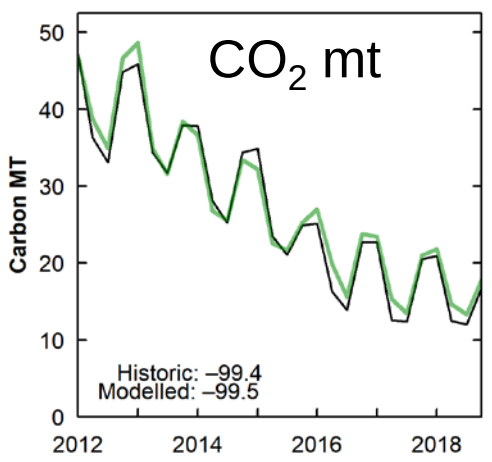
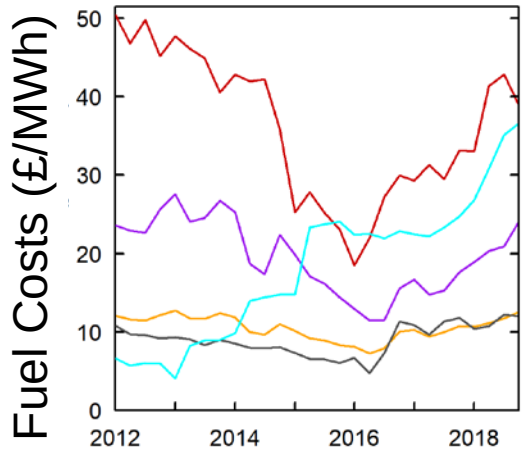
What if…

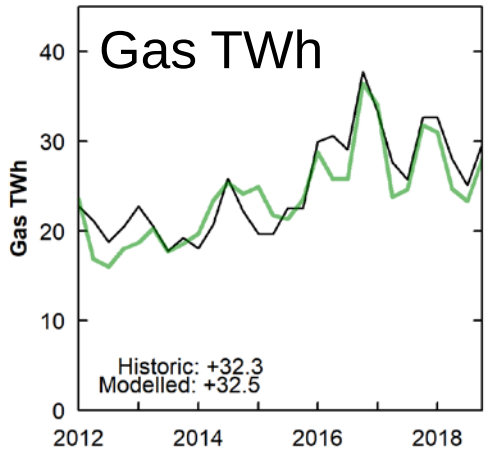
Nothing was fixed?

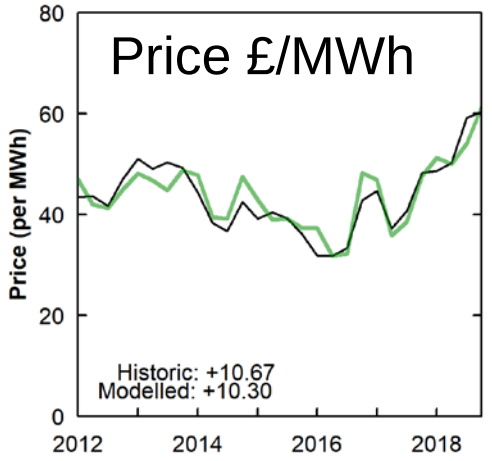












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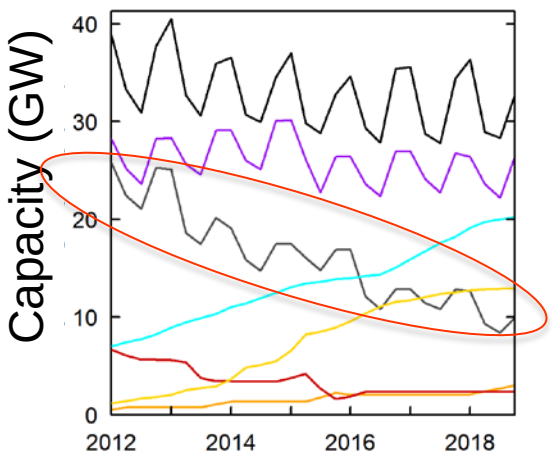
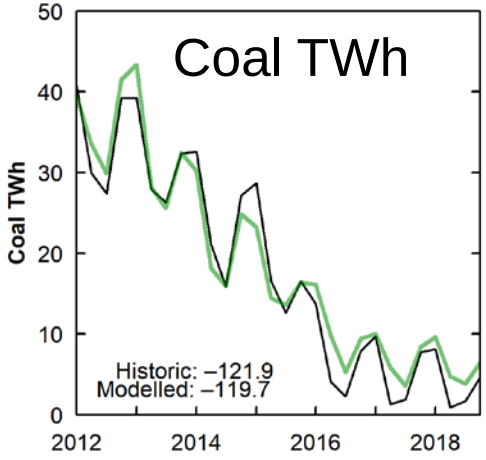
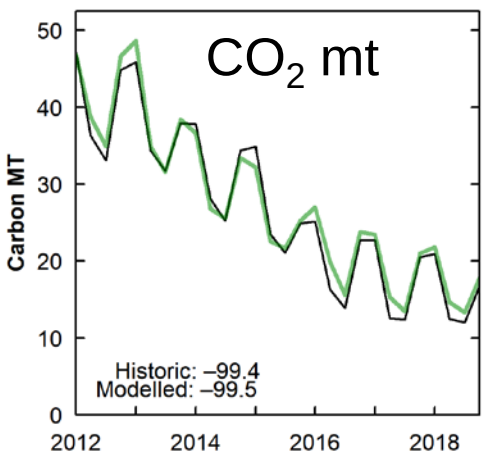
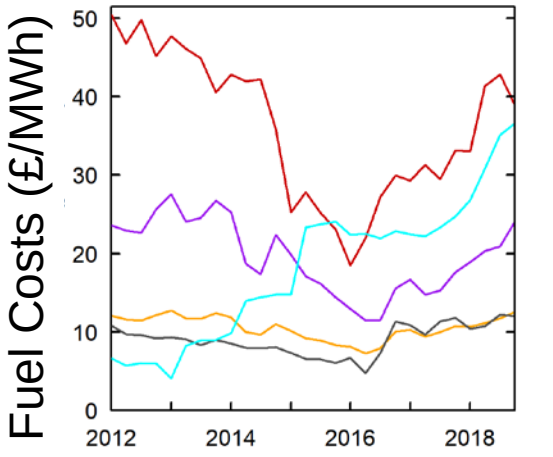
What if…

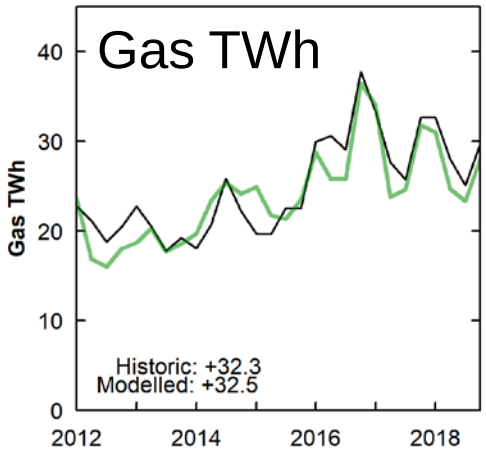
Fossil capacity was fixed?

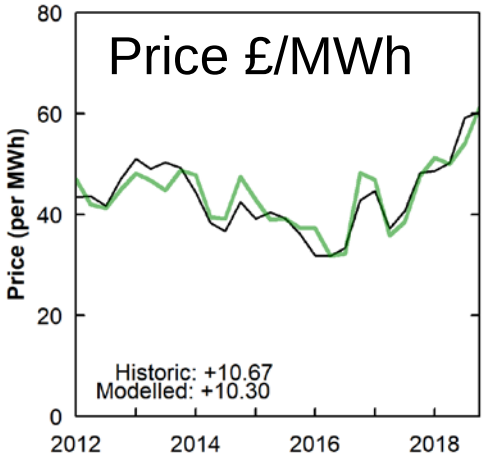












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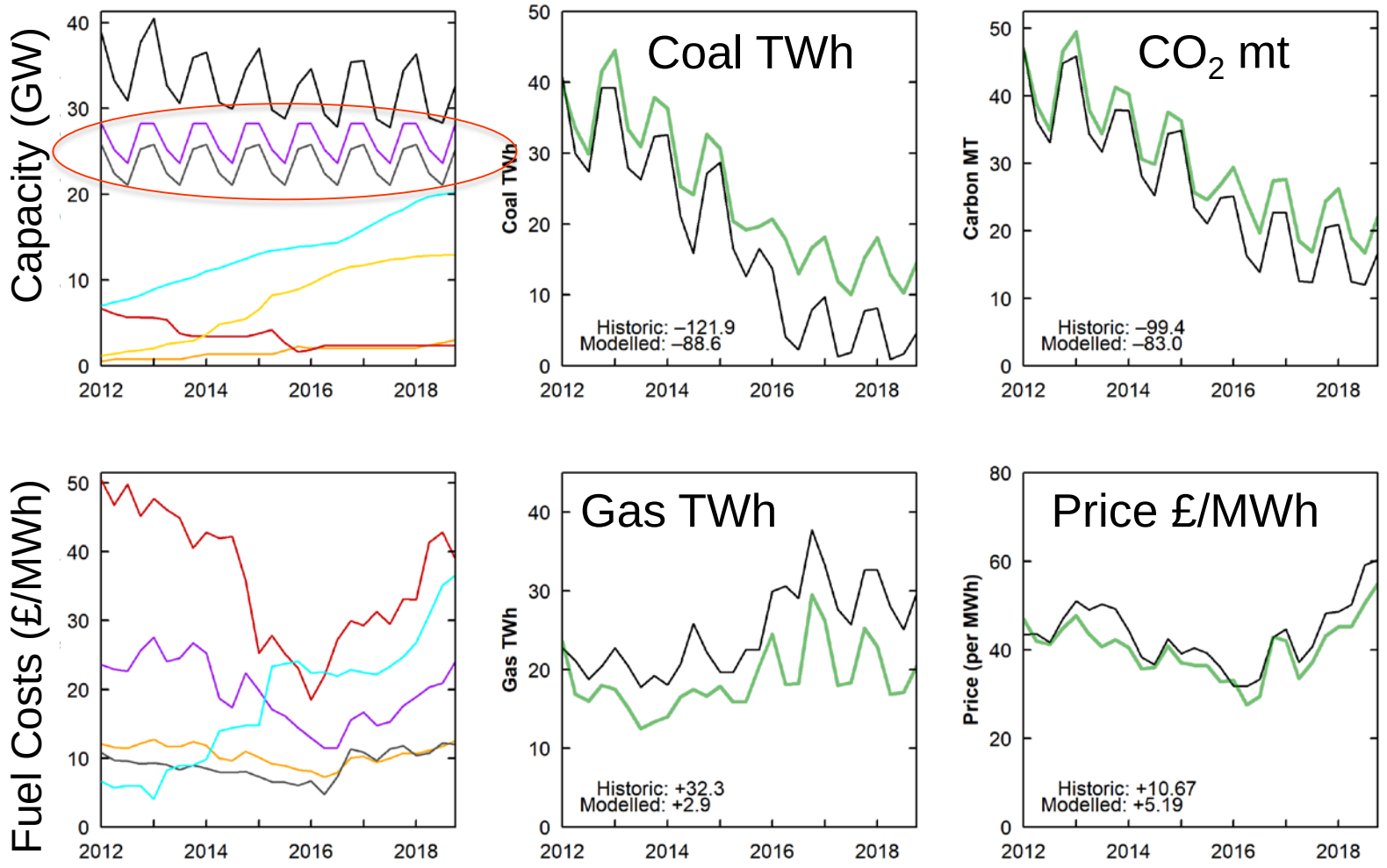
What if…

Fossil capacity was fixed?



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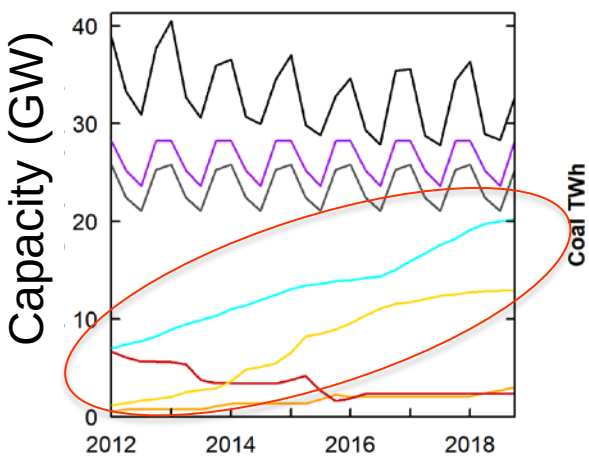
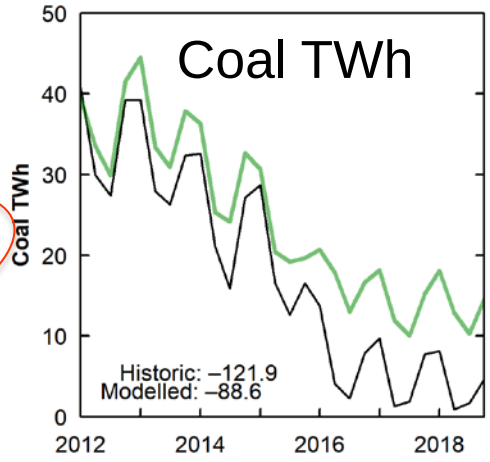
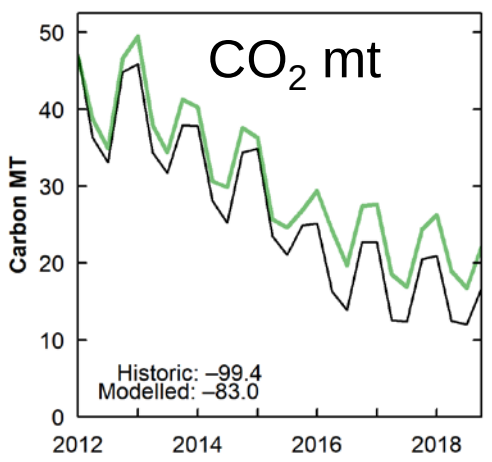
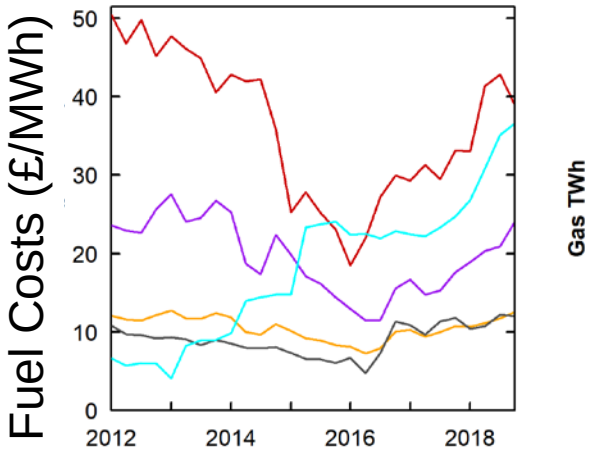
What if…

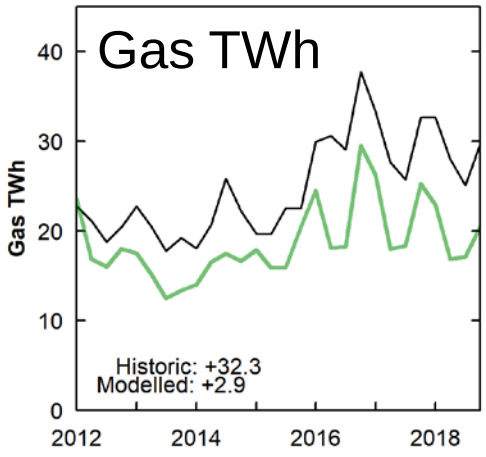
Fossil and renewable capacity was fixed?

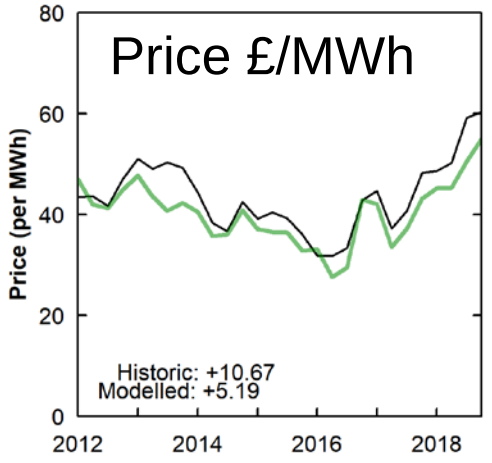












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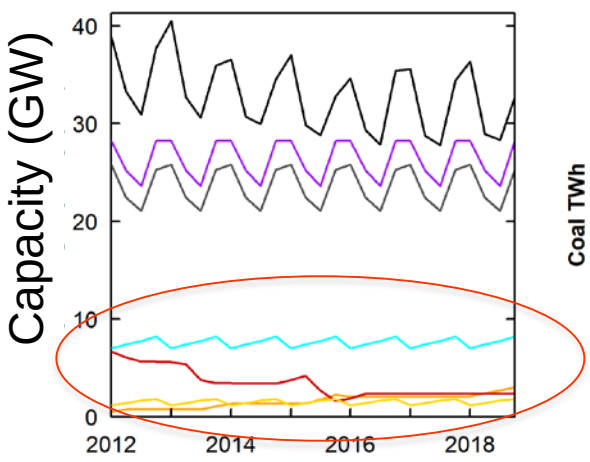
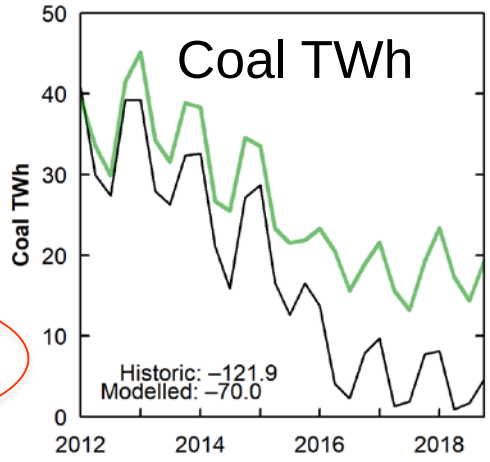
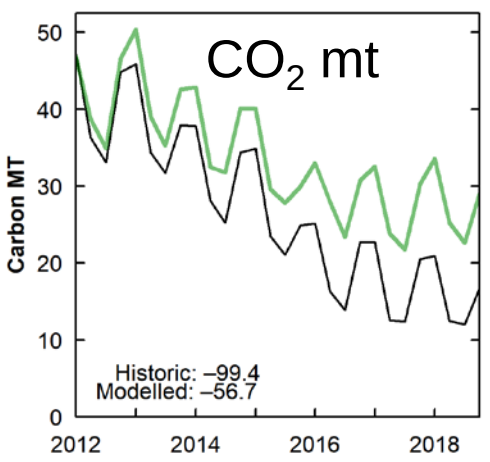
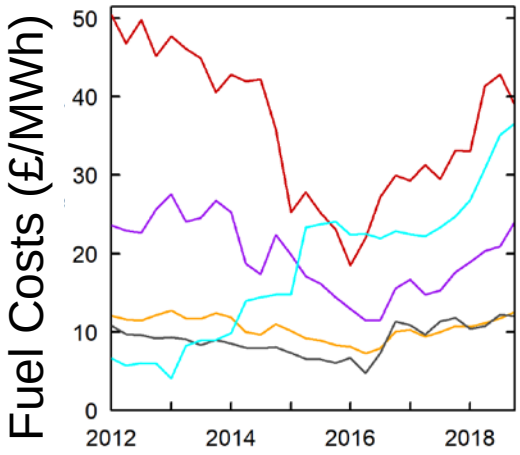
What if…

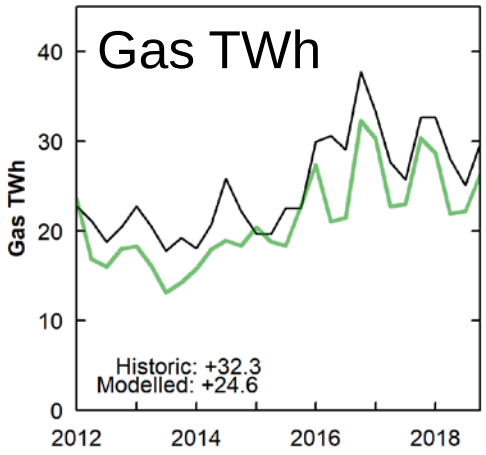
Fossil & renewable capacity was fixed?

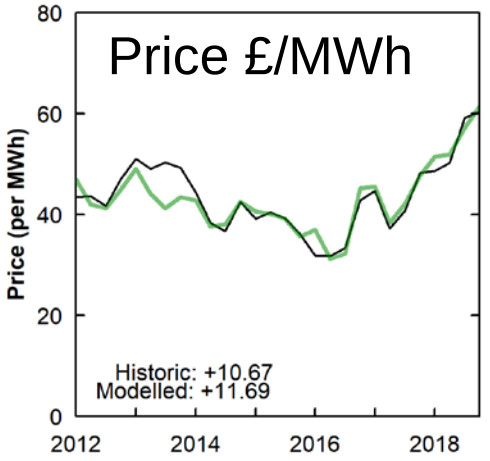












Drivers of emissions

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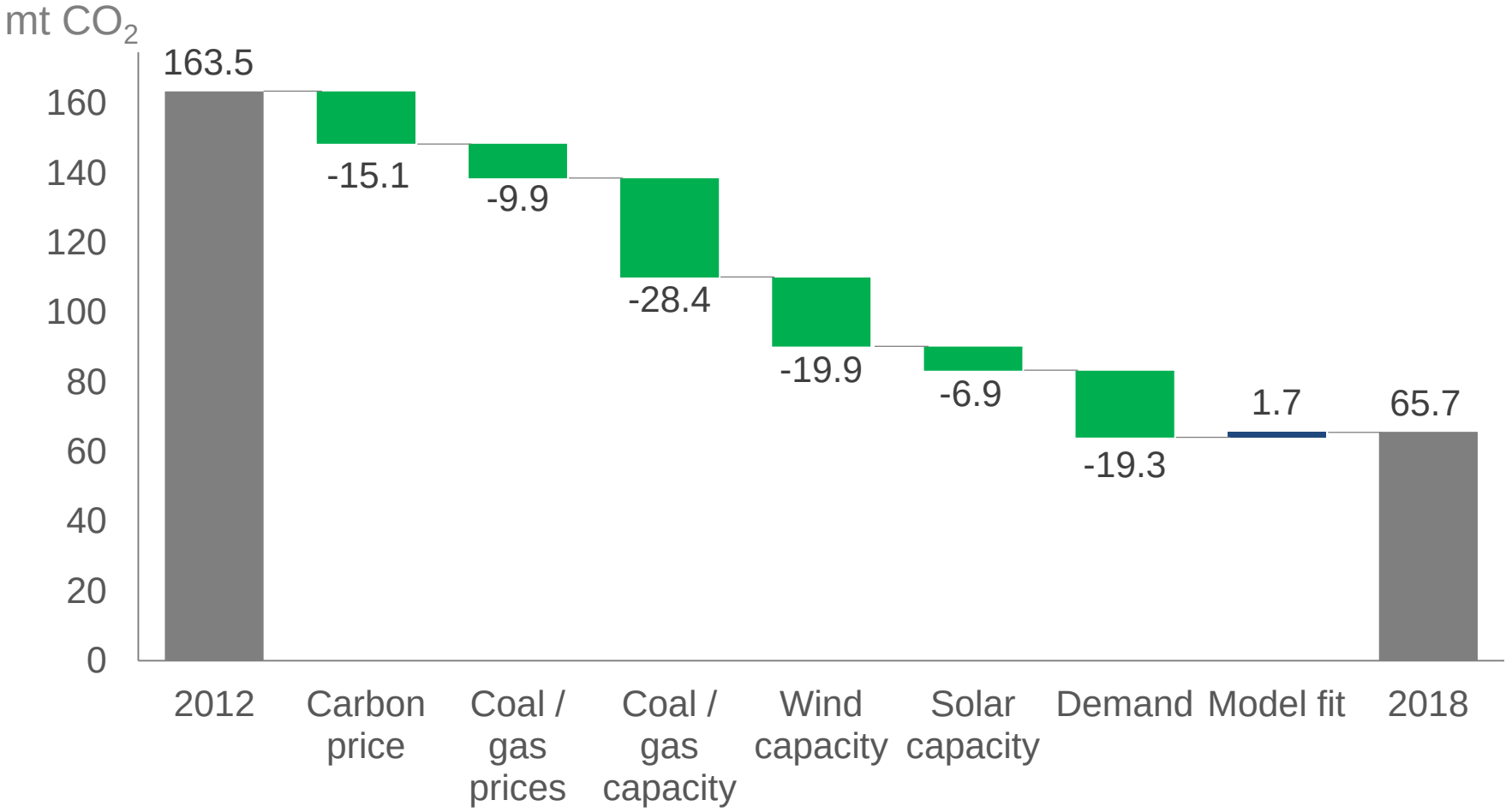
The drivers of emissions

Great Britain, 2012-2018



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The drivers of emissions

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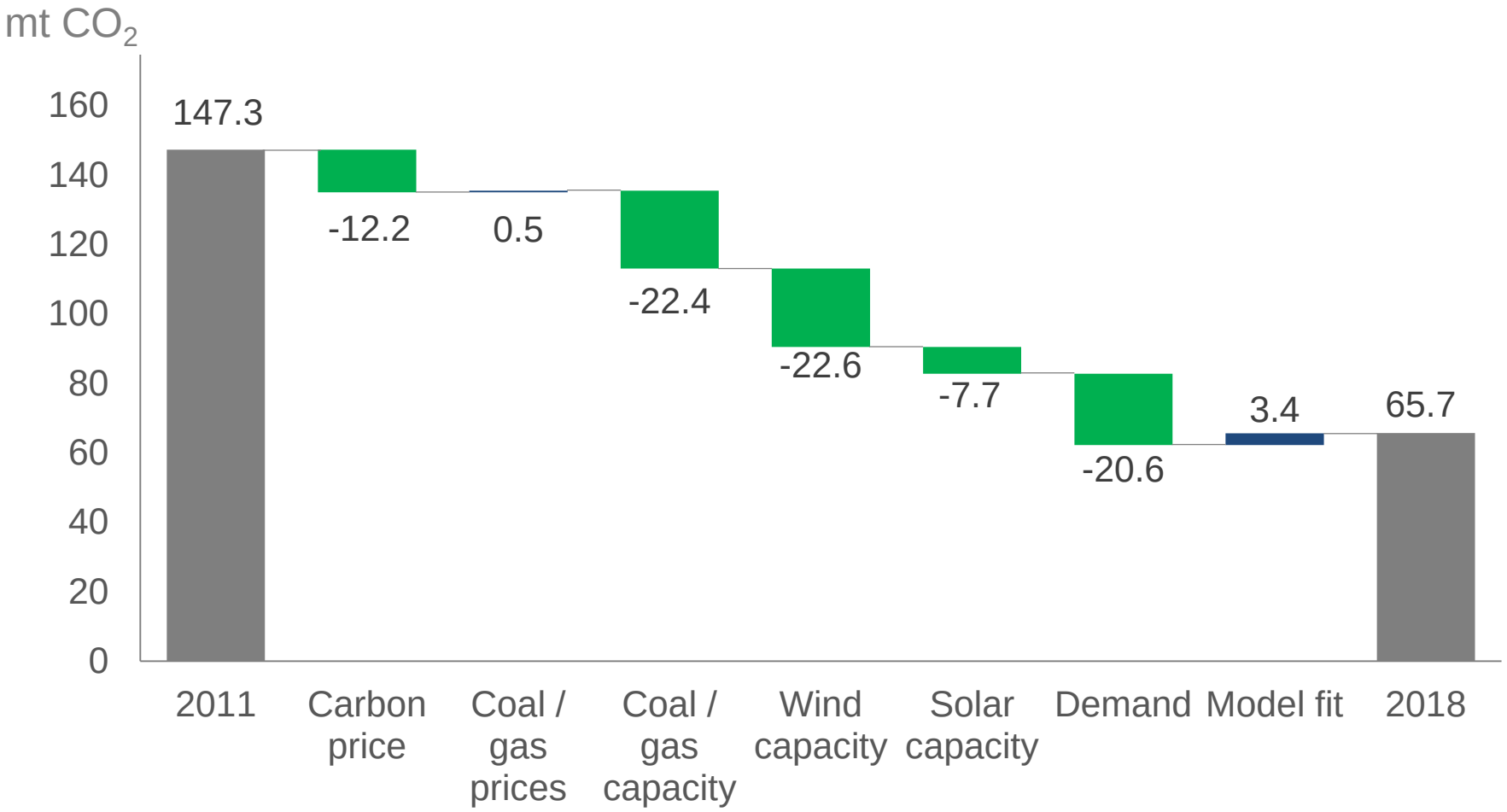

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“Non-marginal” emissions

g/kWh kg/MWh tonnes/GWh	Basis for comparison:	
	2018 vs 2012	2018 vs 2011
Wind	-582	-620
Solar	-668	-674
Demand	750	835

Gas intensity: 394 tCO_2/GWh

Coal intensity: 937 tCO_2/GWh

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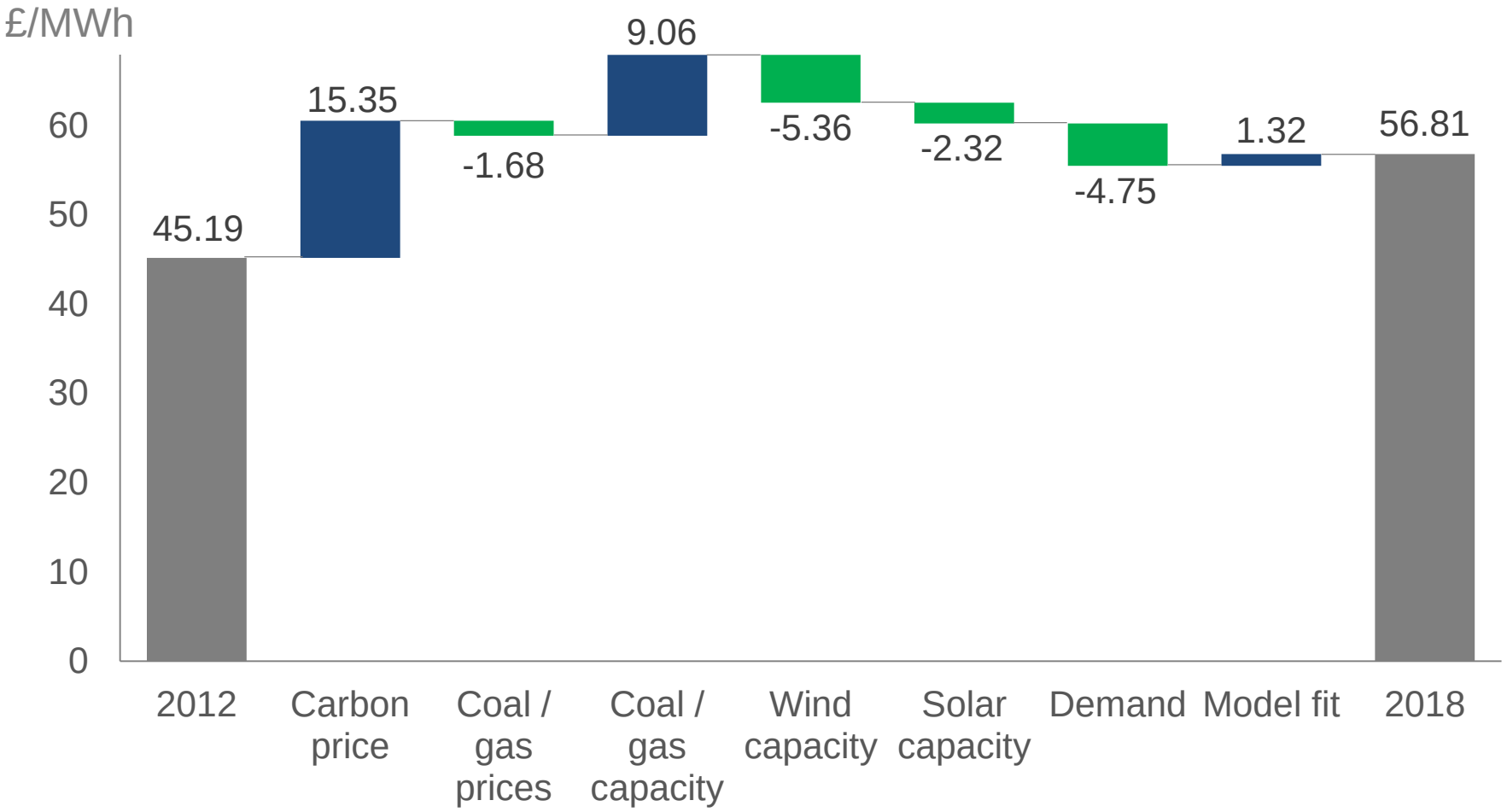
The drivers of price changes

Great Britain, 2012-2018



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Renewable Subsidies

- 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"

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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 £4.6/MWh (market-wide)

- Solar subsidy of £80/MWh (of PV output)
- Merit Order Effect of £2.32/MWh (market-wide)
- Overall impact: increase of £0.5/MWh (market-wide)

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Cost of carbon reductions

- NB this uses subsidy rather than resource cost of wind and solar
  - Changes in coal and gas output assigned via Shapley values and costed at 2018 fuel prices
  - No attempt to consider impact of demand responses

- Wind saved 20 m tonnes CO_2 for £90/tonne
- PV saved 7 m tonnes CO_2 for £60/tonne
- Carbon prices saved 15 m tonnes CO_2 for £14/tonne

Thank you