Marginal curtailment spill-overs of Variable Renewable Electricity: implications

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CEEPR & EPRG European Energy Policy Conference
Copenhagen
27th September 2024

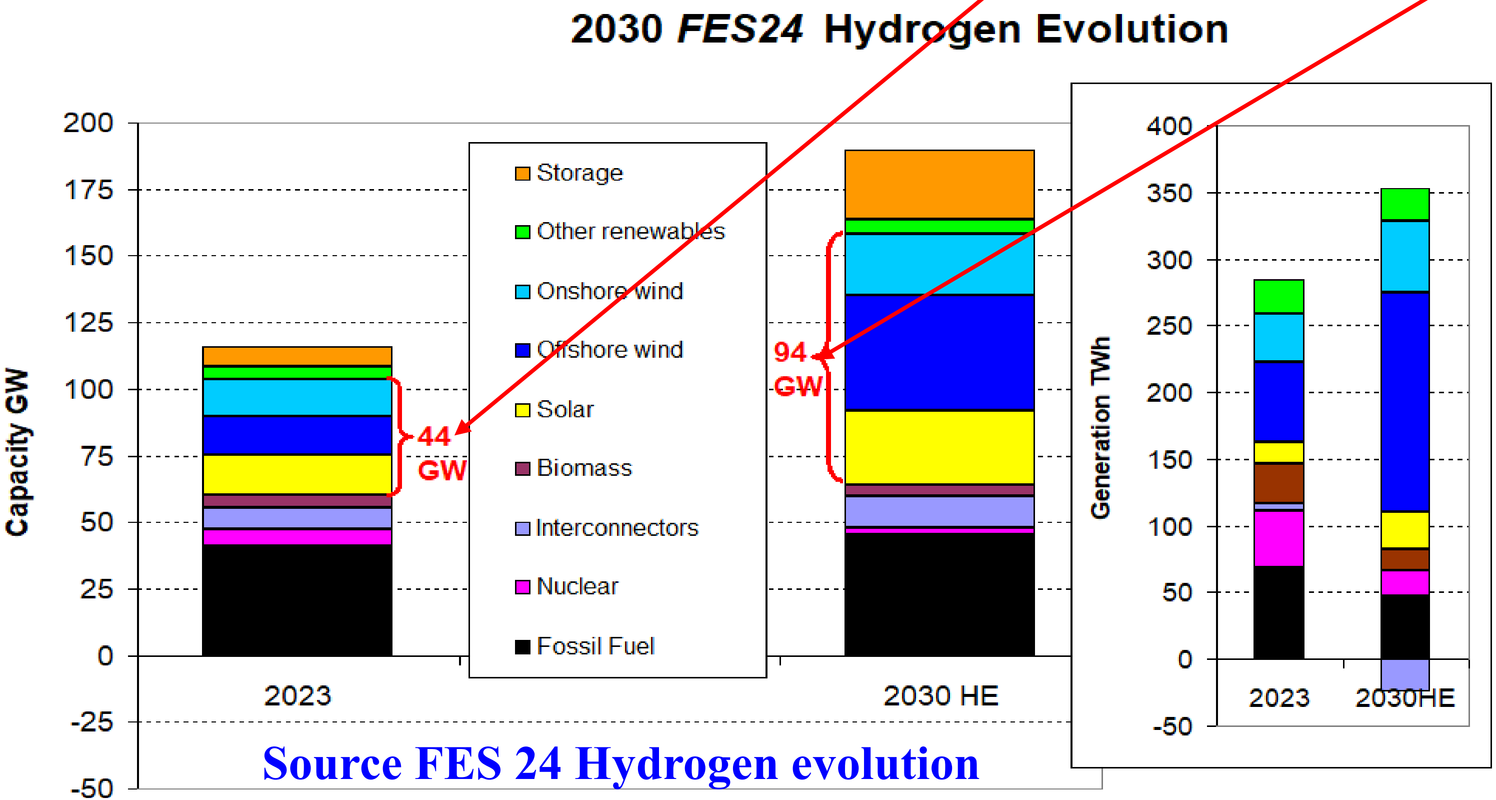
Summary

- Ambitious 2030 targets for GB Variable Renewable Electricity (VRE)
  - PV up 83%, onshore wind 69%, offshore wind ***195%*** from 2023
  - Is this the least-cost portfolio? How do we judge?
- Marginal curtailment = 3+ times average curtailment
  - If average curtailment = 14% an additional MW is curtailed 50% of the time
  - 1 MW extra technology causes more curtailment of ***all*** VRE
- 1 MWh more nuclear => VRE curtailment
  - Equivalent VRE expansion leads to far more curtailment

=> ranking cost per extra MWh delivered may differ from LCoE ranking

Optimal expansion portfolio depends on marginal VRE curtailment

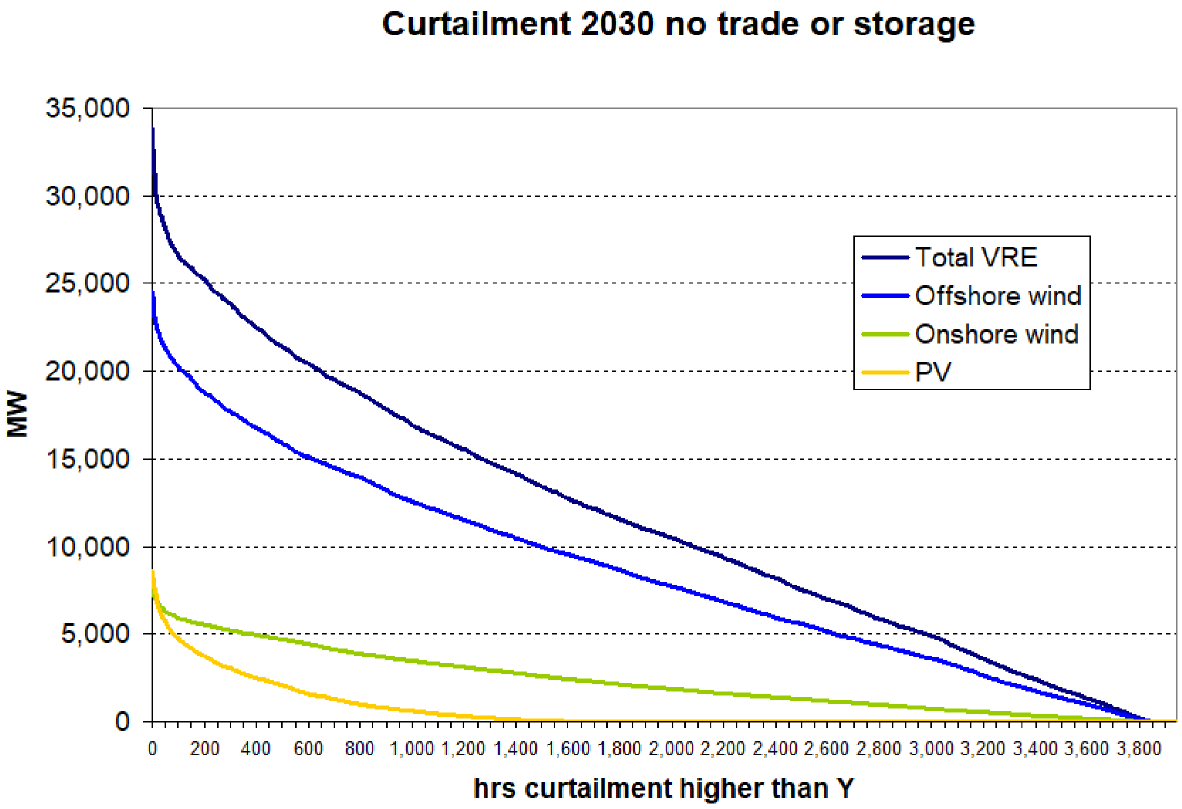
UK VRE capacity to *double* by 2030 in 7 years



Source FES 24 Hydrogen evolution

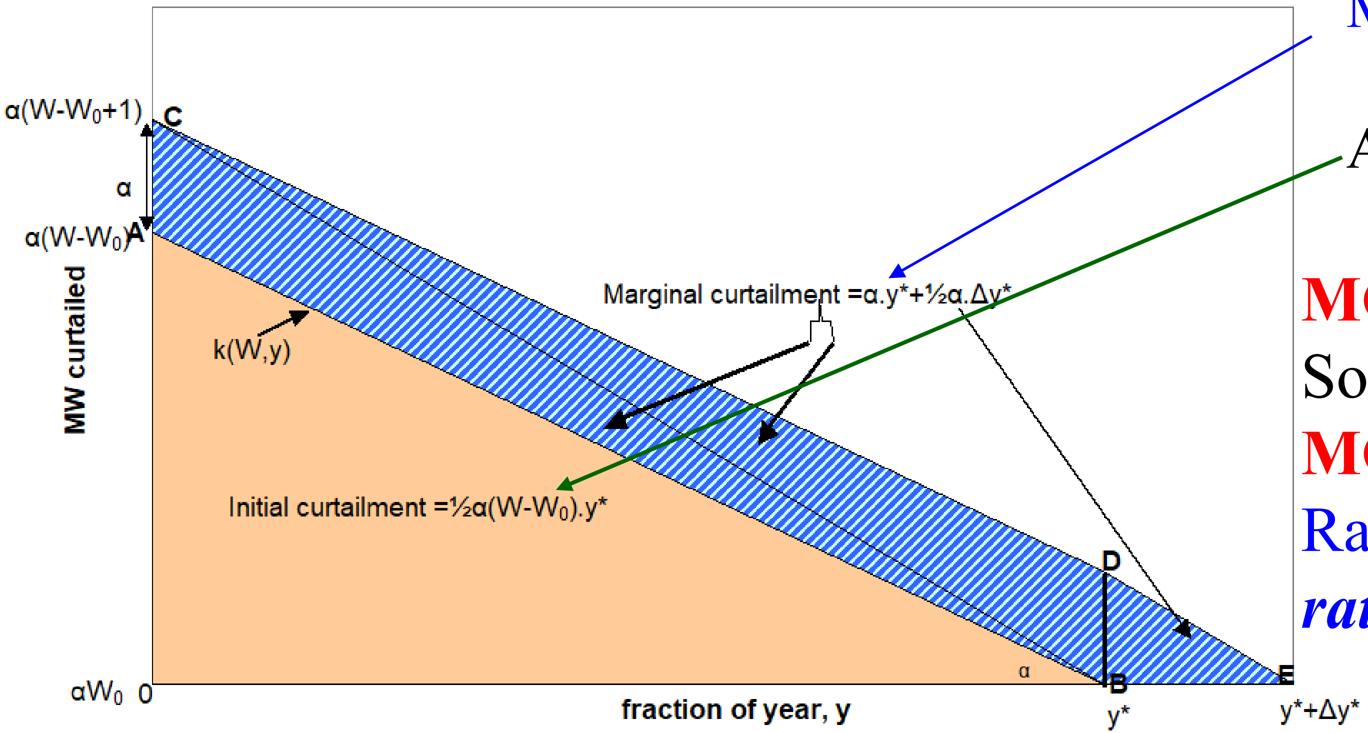
PV, on- and off-shore wind *all* expand

Curtailment curves for each technology GB *Hydrogen evolution scenario*



Each separately ranked – not additive

Ratio of marginal to average curtailment



$MC = \alpha y^*$

$AC = \frac{1}{2}\alpha\,(W-W_0)y^*/W$,

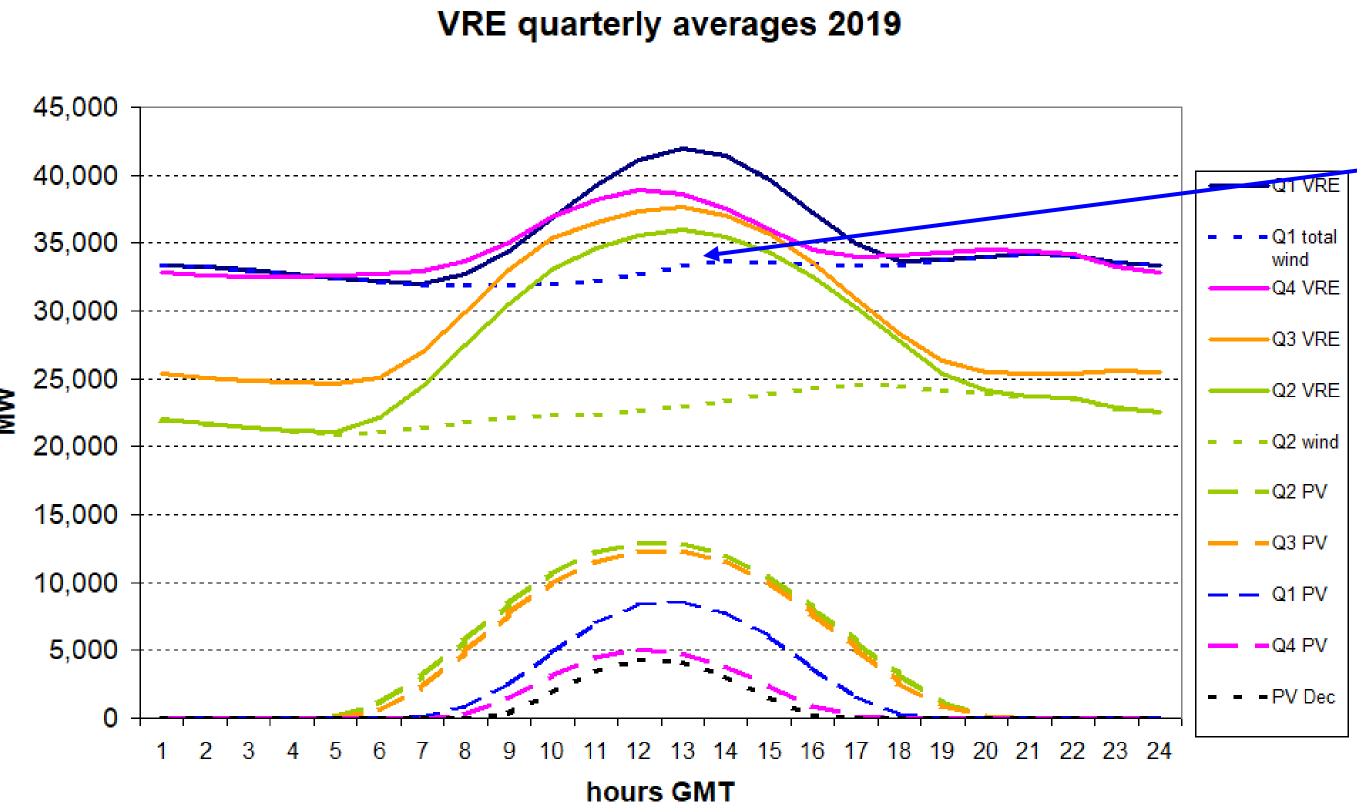
$MC/AC = 2W/(W-W_0)$

So if $W=2W_0$

$MC/AC=4$.

Raising W_0 ***raises ratio***.

GB hourly average wind and PV 2019

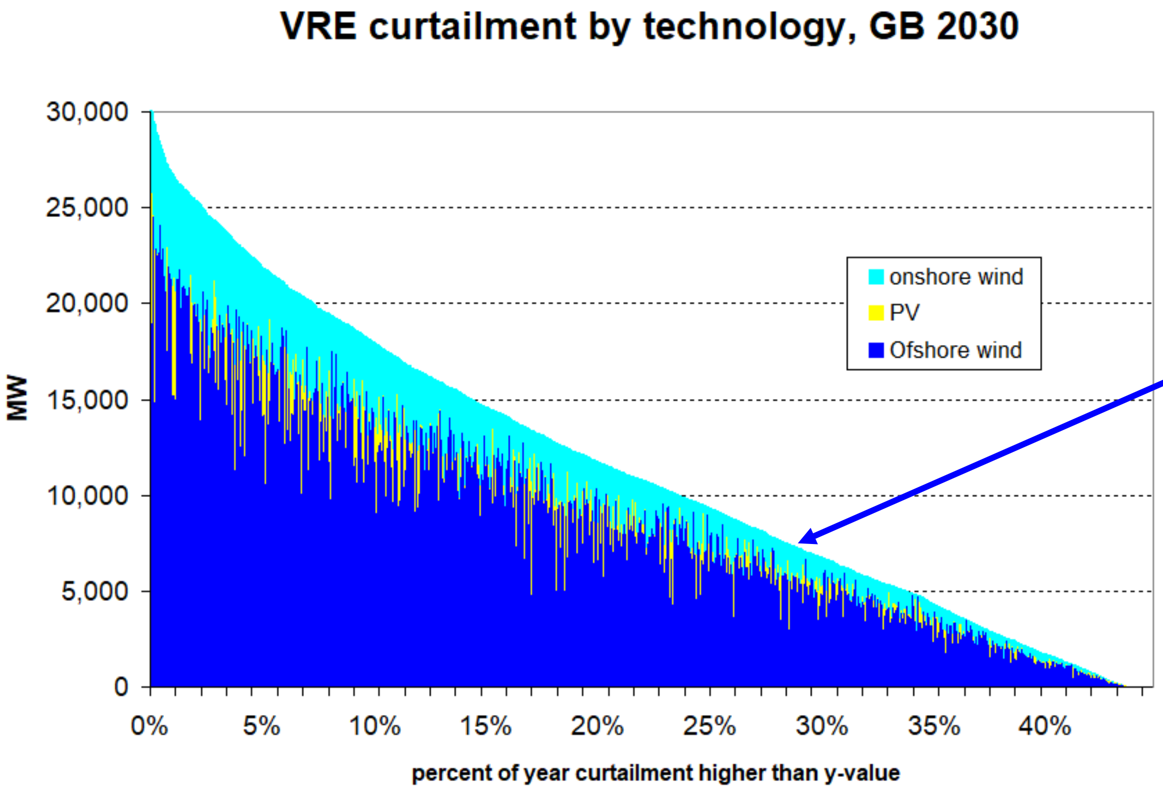


Average wind uniform over day

PV causes mid-day peak VRE

VRE curtailment *HE* 2030 scenario

No trade no storage



Curtailment is ranked by total VRE to make interactions clearer

Simulating 2030

- ESO (2024) *Future Energy Scenarios* projects 2030 GW, GWh/yr
  - For GB and European countries by technology (wind, PV)
- ENTSO-E gives hourly output by technology for 2019
  - NGESO gives GB hourly output by technology for 2019
  - Offshore hourly wind output by site projected from Grothe et al (2022)
- Scale 2019 hourly outputs to 2030 *Hydrogen Evolution* levels
- Curtailment = Max{VRE-(**D**emand *incl. storage, exports*-**N**uclear),0}
  - With some additional benefit that exports and pump storage relaxes curtailment
- Export if curtailed up to Min{IC capacity, neighbour D-VRE-N}
- Store if still curtailed up to remaining storage capacity
- Repeat for remaining curtailment after increasing VRE, nuclear

First examine curtailment without storage and trade

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2030 Results: no storage no trade

	nuclear	Total VRE	OFF	ON	PV	hrs
baseline curtailment MWh	0	45,070,720	33,482,866	8,978,628	2,609,225	3,540
baseline cap MW	2,222	94,089	43,365	23,081	27,644	
av. curtailment MW/cap		424	772	389	94	
capacity increment MW	0	100	100	0	0	
incremented curtailment		45,363,200	33,722,588	9,019,950	2,620,663	3,863
delta		292,481	239,721	41,321	11,438	323
marg curtail/MW VRE		2,925	2,397	413	114	
ratio marg:av			3.79			
capacity increment MW	0	100	0	100	0	
incremented curtailment		45,217,640	33,560,493	9,041,179	2,615,968	3,855
delta		146,920	77,626	62,551	6,743	315
marg. curtail/MW VRE		1,367	737	568	62	
ratio marg:av				3.51		
capacity increment MW	0	100	0	0	100	
incremented curtailment		45,110,111	33,500,809	8,984,260	2,625,041	3,853
delta		39,391	17,943	5,632	15,816	313
marg. curtail/MW VRE		394	179	56	158	
ratio marg:av					4.17	
capacity increment MW	100	0	0	0	0	
incremented curtailment		45,075,128	33,486,546	8,979,349	2,609,233	3,852
delta		4,409	3,680	721	8	312
marg. curtail/MW nuclear		44	37	7	0	

Av. OFF curtailment = 772 MWh/MW

1 MW extra OFFshore wind causes
2,397 MWh curtailment OFF 239,721/100
413 MWH curtailment Onshore wind
114 MWh curtailment PV

Total = 2,925 MWh curtailed VRE

Marg:average = 2,719/772 = 3.79

Higher for PV

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VRE displaces more CO_2 than nuclear

	nuke	Total VRE	OFF	ON	PV	hrs
capacity increment MW	100	0	0	0	0	
incremented curtailment		45,075,128	33,486,546	8,979,349	2,609,233	3,852
delta		4,409	3,680	721	8	312
marg. curtail/MW nuclear		44	37	7	0	
capacity increment MW	0	416	416	0	0	
incremented curtailment		46,291,763	34,484,458	9,150,507	2,656,799	3,901
delta		1,221,043	1,001,591	171,878	47,574	361
marg. curtail/MW nucl. equiv		12,210	2,410	414	114	
capacity increment MW	0	503	0	503	0	
incremented curtailment		45,812,915	33,874,008	9,295,705	2,643,203	3,885
delta		742,196	391,141	317,076	33,978	345
marg. curtail/MW nucl. equiv		7,422	3,911	3,171	340	
capacity increment MW	0	1,114	0	0	1,114	
incremented curtailment		40,178,815	33,683,309	9,041,625	2,788,694	3,875
delta		442,908	200,442	62,997	179,469	335
marg. curtail/MW nucl. equiv		4,429	2,004	630	1,795	

These increments of VRE give the same average output of 100 MW over the year as the nuclear increment

Marginal costs depend on *marginal capacity factors*

capacity factors, CF	OFF	ON	PV
potential CF	51.6%	27.0%	10.8%
Average CF	42.8%	22.6%	9.7%
MCF of each separately	24.2%	19.9%	9.0%
total MCF incl spillovers	18.2%	10.3%	6.3%
MCF of each, all + 100 MW	13.3%	14.5%	6.9%

← Govt. comparisons of VREs normally use the potential CF to compute the Levelised Cost of Electricity, LCoE

← This marginal capacity factor, MCF, is that of incrementing each technology by 100 MW

← This MCF is for a uniform increase of each technology by 100 MW

Note: no trade nor storage

LCoEs and CfD auctions fail to indicate least cost choices

technology		VRE	OFF	ON	PV
capacity increment MW		100	39.29	20.86	39.85
fixed cost £/kWyr			£244.30	£126.24	£52.16
LCoE £/MWh		£55.09	£55.09	£55.09	£55.09
cost/MWH delivered		£126.84	£162.81	£152.16	£81.44

Capacity increments to move from 2029 to 2030

Even if the LCoEs are the same, the delivered costs can be very different and could easily give a different ranking of technologies

Note: no trade nor storage

Shifting surplus VRE over time and space

- Curtailment here is a system-wide phenomenon
  - assumes no transmission constraints
  - nuclear power provides most ***inertia*** (> 10% gross demand)
- Surplus VRE can be **exported**
  - ***If*** neighbours have residual demand after VRE
  - up to export **capacity**
- Surplus VRE can be **stored**
  - Pumped storage, batteries, EVs, controlled hot water heating (?)

How significant are these and what impact on marginal cost?

Trade and storage reduce hours curtailed, little effect on peak

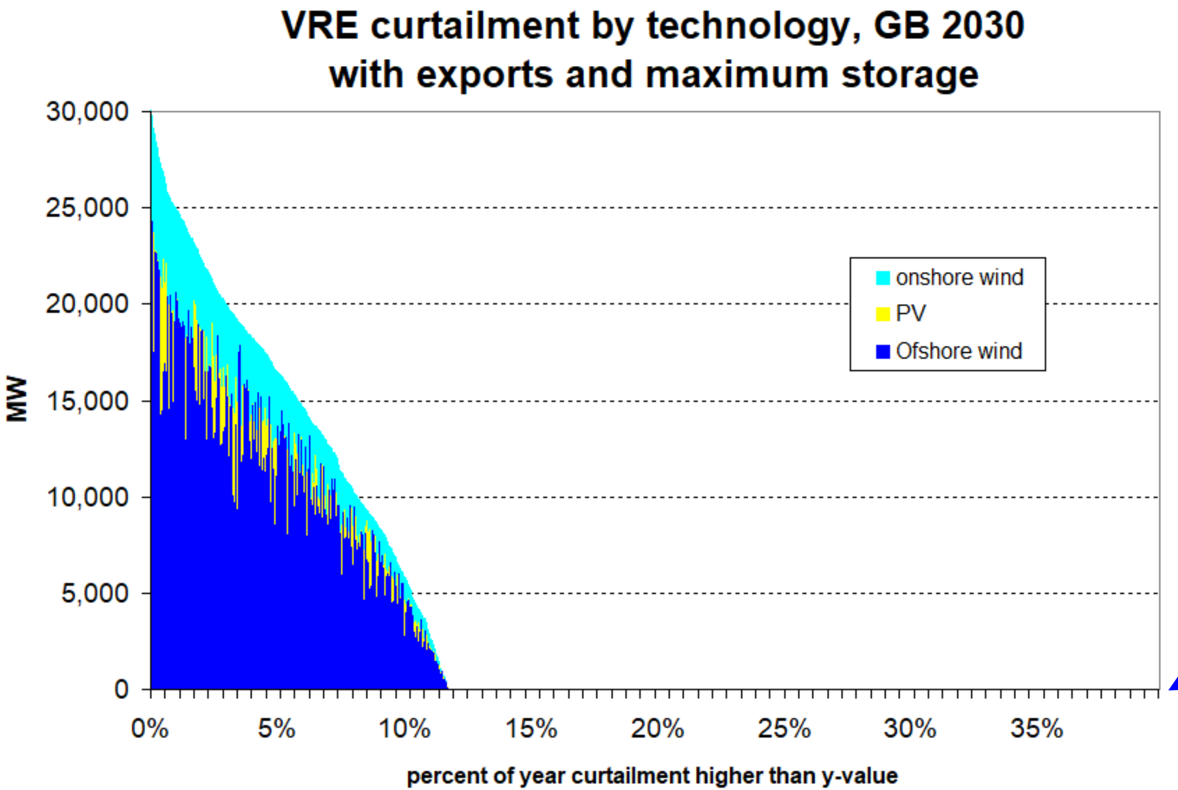

Figure drawn with same axes as before.
With no trade and storage curtailment extends to here

Trade and storage substantially reduce marginal cost of VRE

		VRE	OFF	ON	PV >10MW	PV<50kW
capacity increment		100	39.3	20.9	39.8	39.8
fixed cost £k/kWyr			£199.87	£108.60	£34.34	£50.20
LCoE		£46.53	£47.24	£51.84	£36.27	£53.01
cost/MWH delivered		£50.59	£52.20	£54.22	£38.55	£56.35

Before trade and storage **150-180% more costly** than LCoE (=LCoE/MCF), PV is **50% more**

With trade and storage wind is **5-10% more costly** than LCoE, PV is **6% more**

Capacity increment is that from 2029 to 2030

Conclusions

- As GB moves towards 2030 VRE targets marginal curtailment rates rise rapidly and with them **marginal costs**
  - Before trade and storage marginal costs are **150%-180%** more than LCoEs (**50%** more for PV)
- Storage and trade halve curtailment hours (but not peak)
  - And reduce marginal costs to 5-10% of LCoEs
- Ranking of technology costs can be very different than LCoEs that guide auction results
- Nuclear power displaces less CO_2 than its nominal output
  - But VRE displaces considerable more (except for PV)

Marginal curtailment analysis crucial for least cost choices

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Acronyms

AC:	Average Curtailment
CF:	Capacity Factor
ESO:	Electricity System Operator
EV:	Battery Electric Vehicle
IC:	Interconnector Capacity
HE:	Hydrogen Evolution scenario
LCoE:	Levelised Cost of Electricity
MC:	Marginal Curtailment
MCF:	Marginal Curtailment Factor
VRE:	Variable renewable electricity

References

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Sensitivities

- Order of curtailment matters
  - Efficiency requires highest avoidable cost curtailed first
- Minimum controllable output for stability matters
  - Assume challenging 10% total demand (currently > 25%)
  - Does EV, hot water provide suitable frequency response?
- Speed of VRE penetration in Europe matters
  - More VRE => less ability to export surplus
- Domestic transmission constraints matter
  - Ignored here, will influence what is curtailed
  - Locational pricing then matters for guiding exports

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Efficient curtailment makes a big difference to MC/AC

		nuclear	Total VRE	OFF	ON	PV	hrs
baseline curtailment MWh		0	45,070,720	17,190,456	27,880,263	0	3,540
baseline cap MW		2,222	94,089	43,365	23,081	27,644	
av. curtailment MW/cap			479	396	1,208	0	
capacity increment MW		0	100	100	0	0	
incremented curtailment			45,363,200	17,383,851	27,979,350	0	3,863
delta			292,481	193,394	99,086	0	323
marg curtail/MW VRE			2,925	1,934	991	0	
ratio marg:av				7.38			
capacity increment MW		0	100	0	100	0	
incremented curtailment			45,217,640	17,190,456	28,027,184	0	3,855
delta			146,920	0	146,920	0	315
marg. curtail/MW VRE			1,469	0	1,469	0	
ratio marg:av					1.22		
capacity increment MW		0	100	0	0	100	
incremented curtailment			45,110,111	17,216,303	27,893,807	0	3,853
delta			39,391	25,847	13,544	0	313
marg. curtail/MW VRE			394	258	135	0	
ratio marg:av						n.a.	

Efficiency curtails onshore wind first, then offshore, finally PV (decreasing order of avoidable cost)

Further curtailment falls on offshore wind