Zonal pricing, transmission constraints and impacts on VRE curtailment

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E&E seminar CJBS

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Summary

- 2030 targets for GB Variable Renewable Electricity (VRE)
  - PV up 83%, onshore wind 69%, offshore wind ***195%*** from 2023

1. Study island of Ireland with single VRE (wind)
   - empirically marginal curtailment (*mc*) = 3+ times *ac*

   => If *ac* = 14% an additional MW is curtailed 50% of the time
2. 1 MW extra single VRE causes more curtailment of ***all*** VRE

   ⇒ E.g. expand offshore wind => curtail onshore wind and PV

   ⇒ **Amplifies** *mc* in study of copper plate GB connected to EU
3. This study: examine internal congestion in GB

   ⇒ **Further amplifies** *mc* : VRE limited by transmission limits => local curtailment

   – Seven zones as in **Zonal pricing study**

   ⇒ exports spill over to neighbouring zones => additional curtailment
4. Calculates long-run marginal costs by zone

   ⇒ **Do not expand renewables in Scotland**

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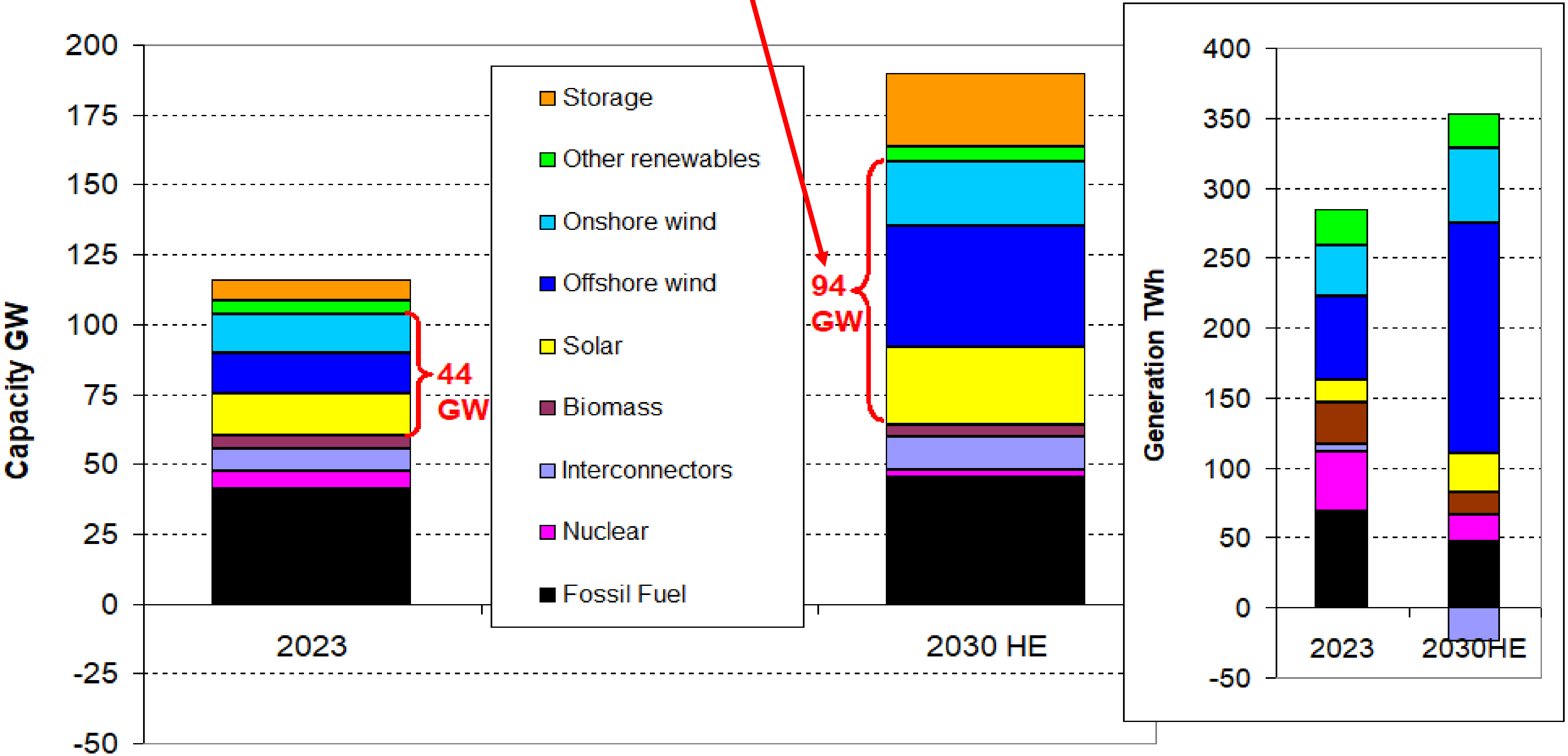
UK VRE capacity to *double* by 2030 in 7 years

2030 *FES24* Hydrogen Evolution



Transmission congestion curtails Scottish wind

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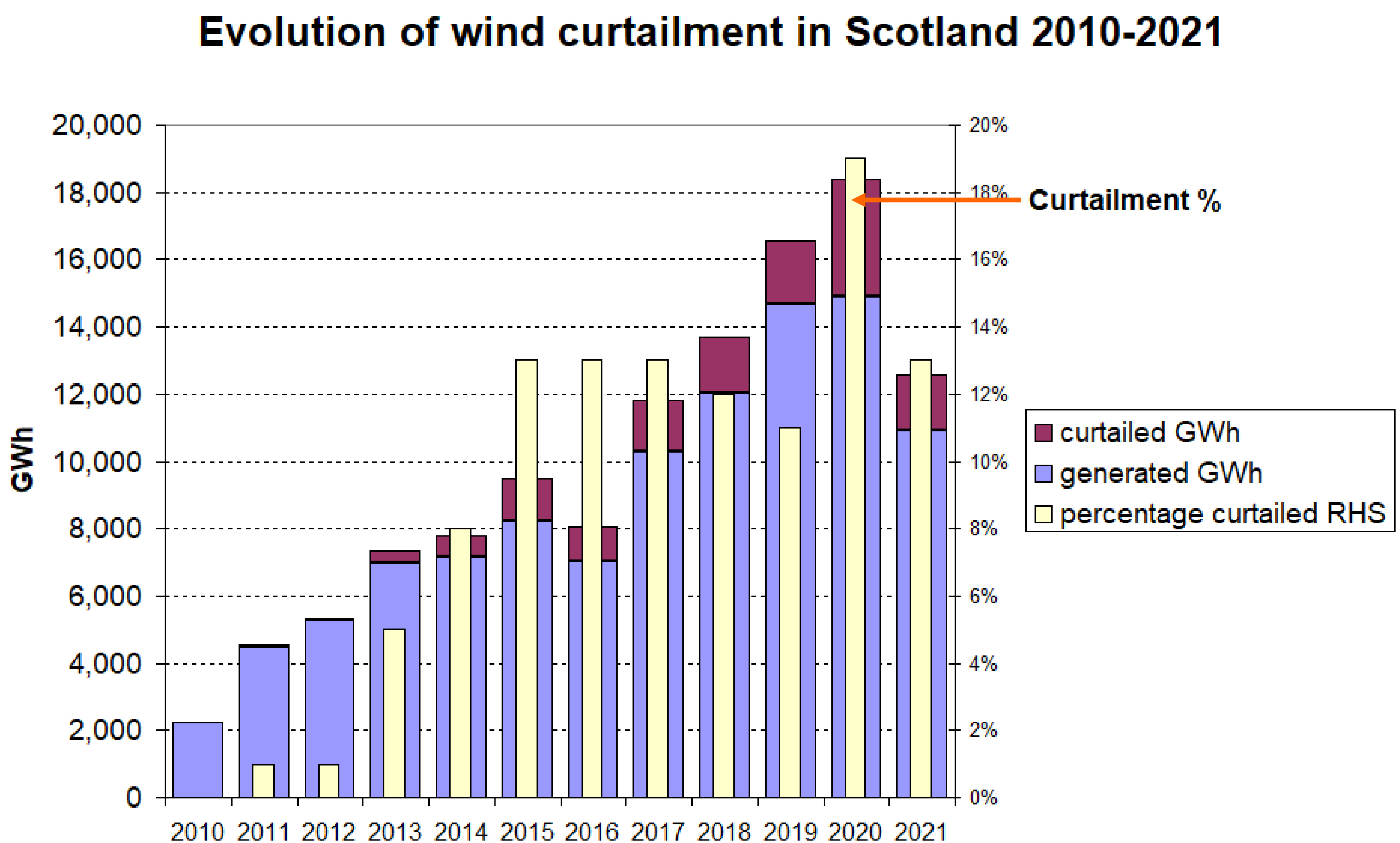

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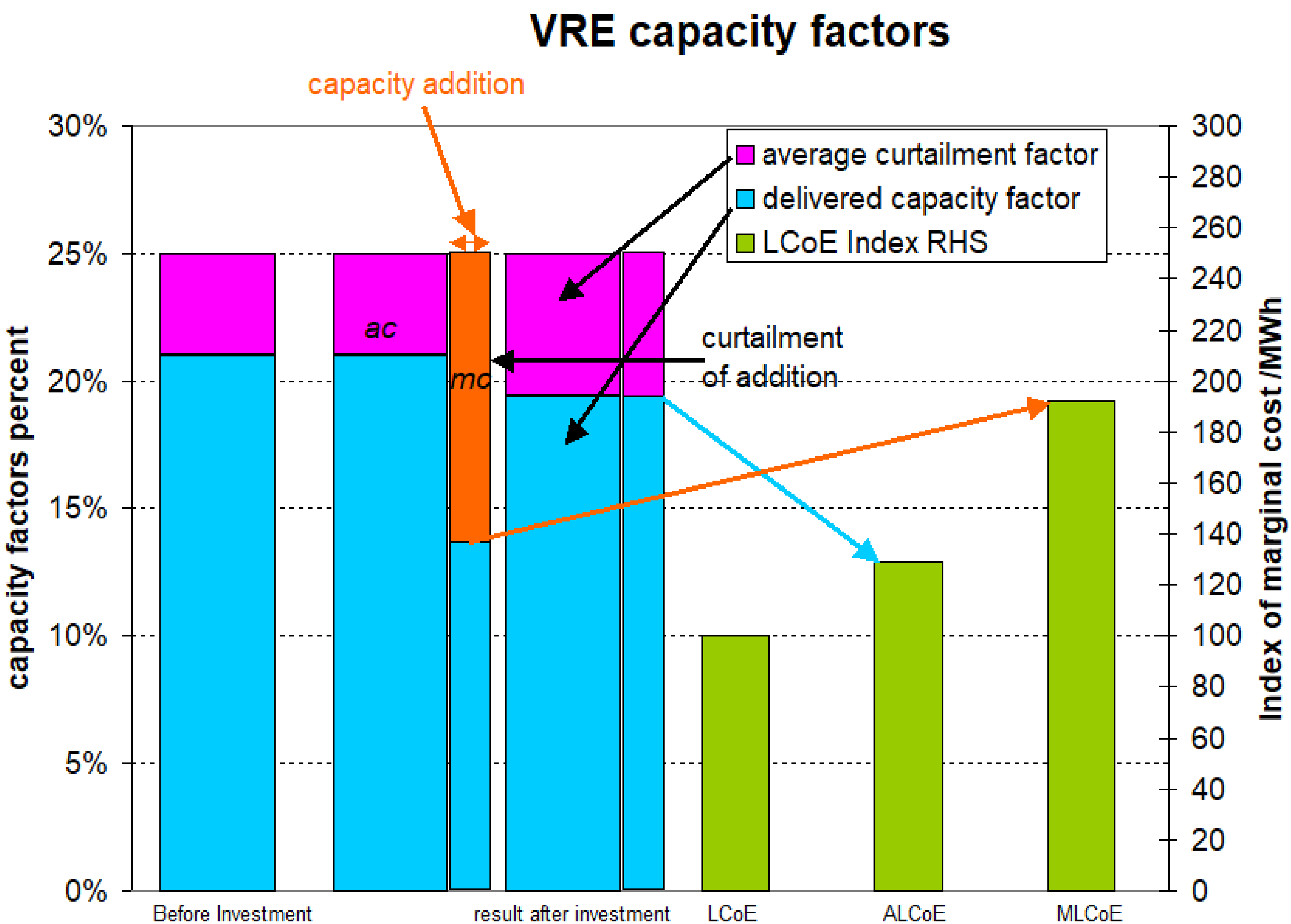
Average vs marginal curtailment and cost implications



Long-run marginal cost

- Levelised cost of electricity LCoE = $F/(8760 \times PCF) + v$
  - F is annualised fixed cost per £/MW, v is variable cost £/MWh
  - PCF is potential capacity factor as % so *8760= hrs per year
- long-run average cost (LACoE) = $F/(8760 \times ACF) + v$

$\Rightarrow$ LACoE ≈ LCoE*PCF/ACF, ACF = (1 – ac)*PCF

$\Rightarrow$ LACoE/LCoE ≈ 1/(1 – ac)

$\Rightarrow$ Long-run marginal cost, LMCoE ≈ LCoE/(1 – mc)

$\Rightarrow$ As mc increases so does marginal cost of investing

- ***Need to measure <u>marginal</u> not average curtailment***
  - ***Need to revisit VRE support designs***

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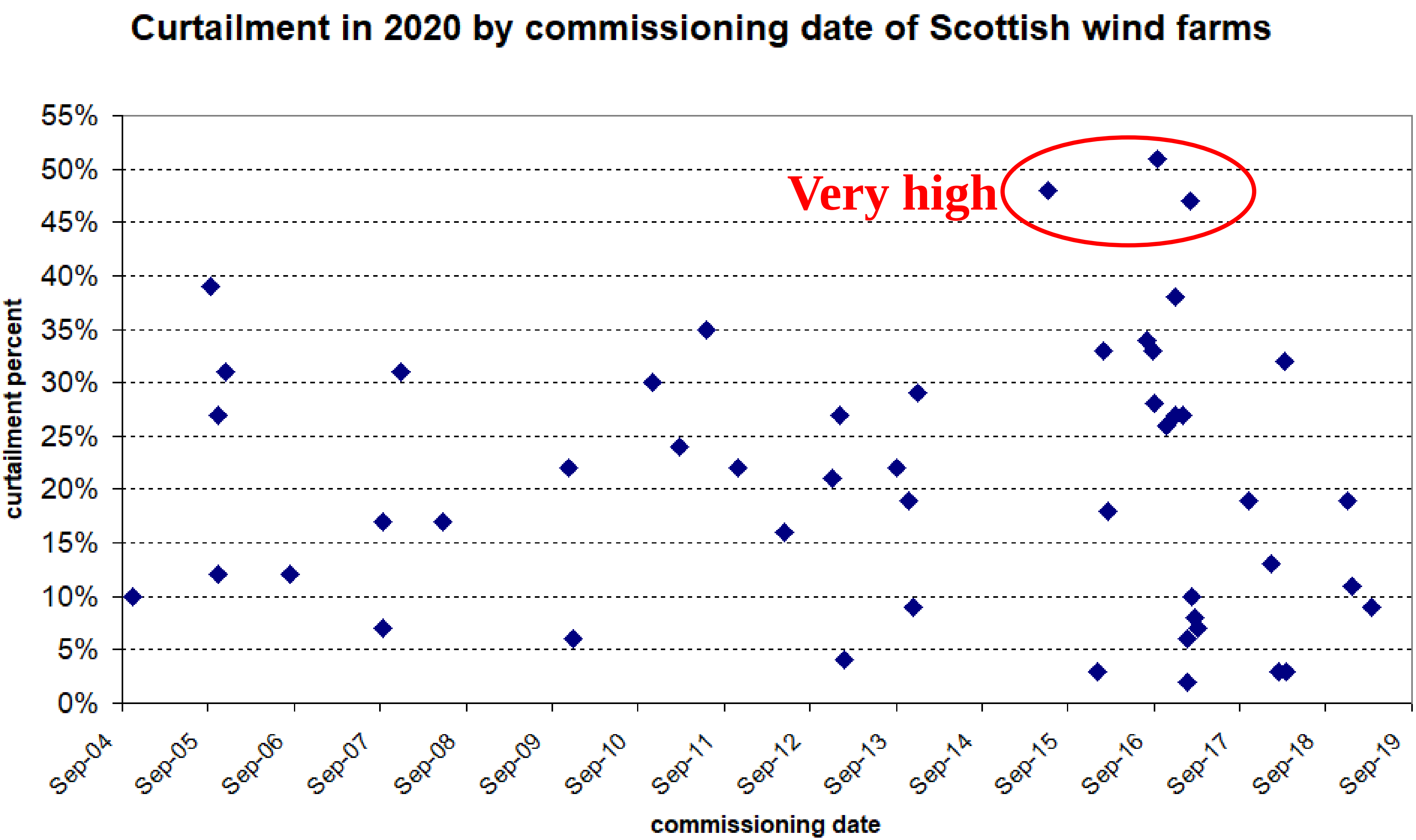
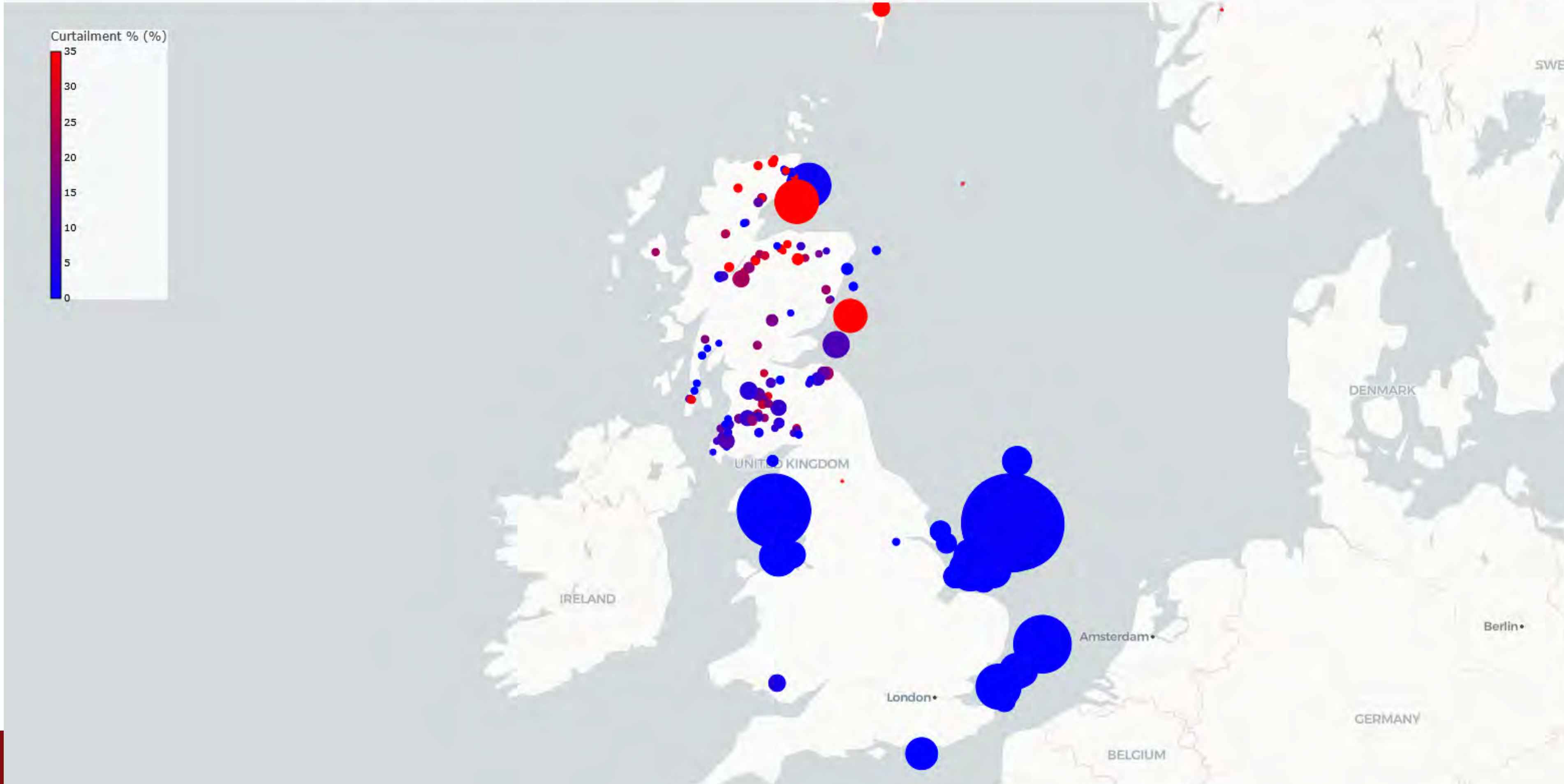
Scotland transmission constraints already very serious before 2020

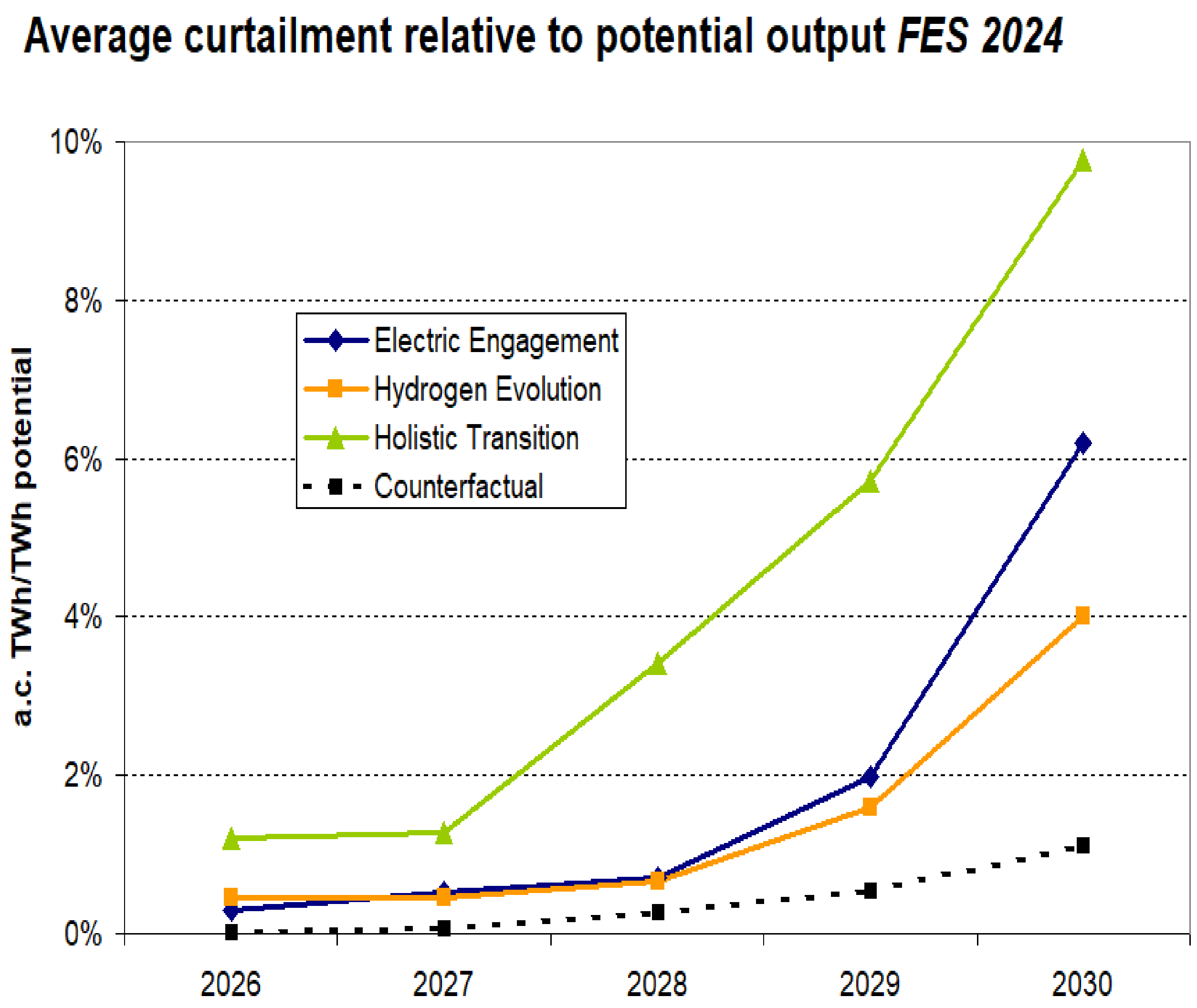


Curtailment percentages 2024

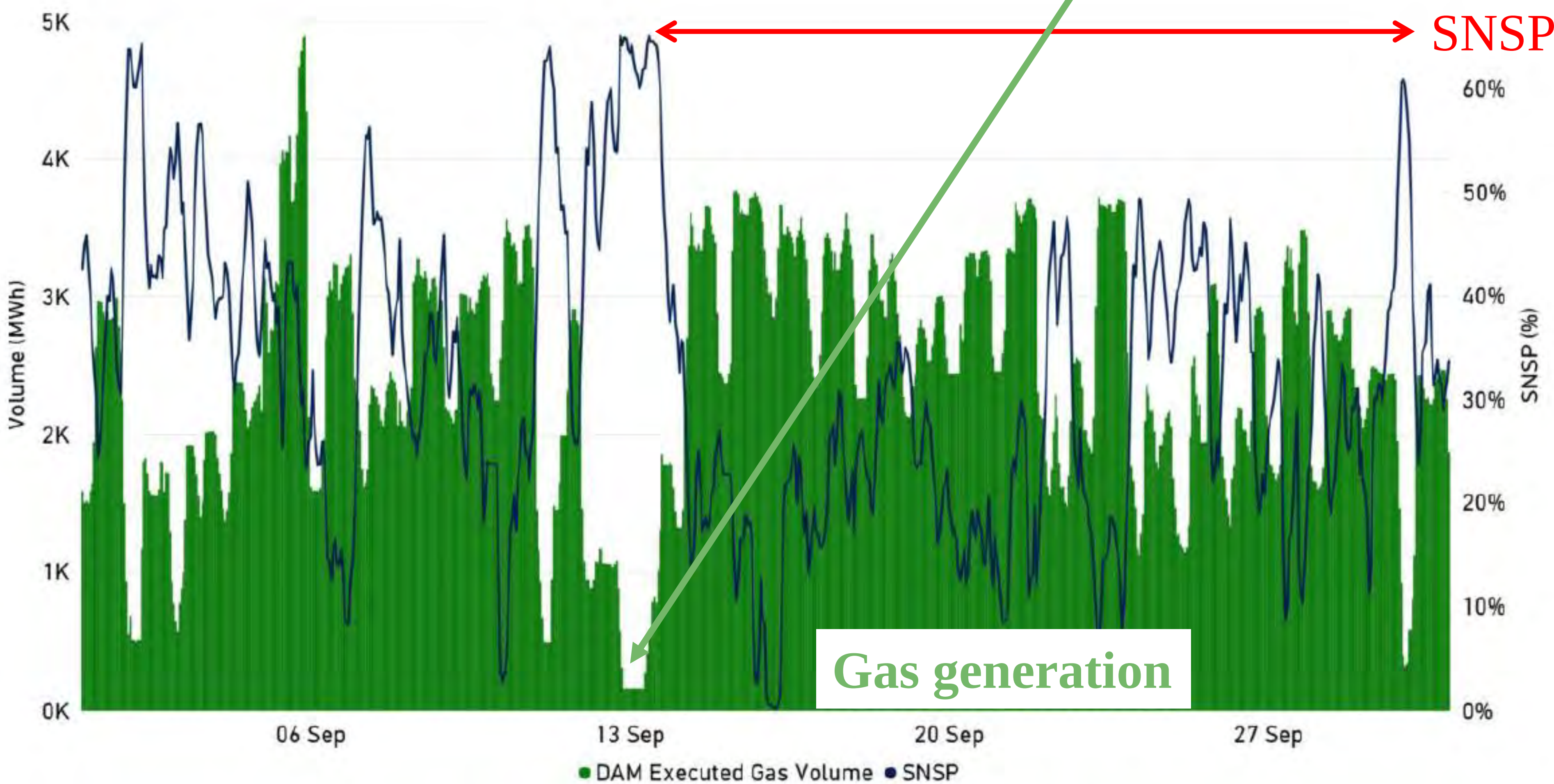
Curtailment: a Scottish phenomenon in 2025, expected to increase byj 2030



ESO (2024) Future Energy Scenarios shows rising *ac*



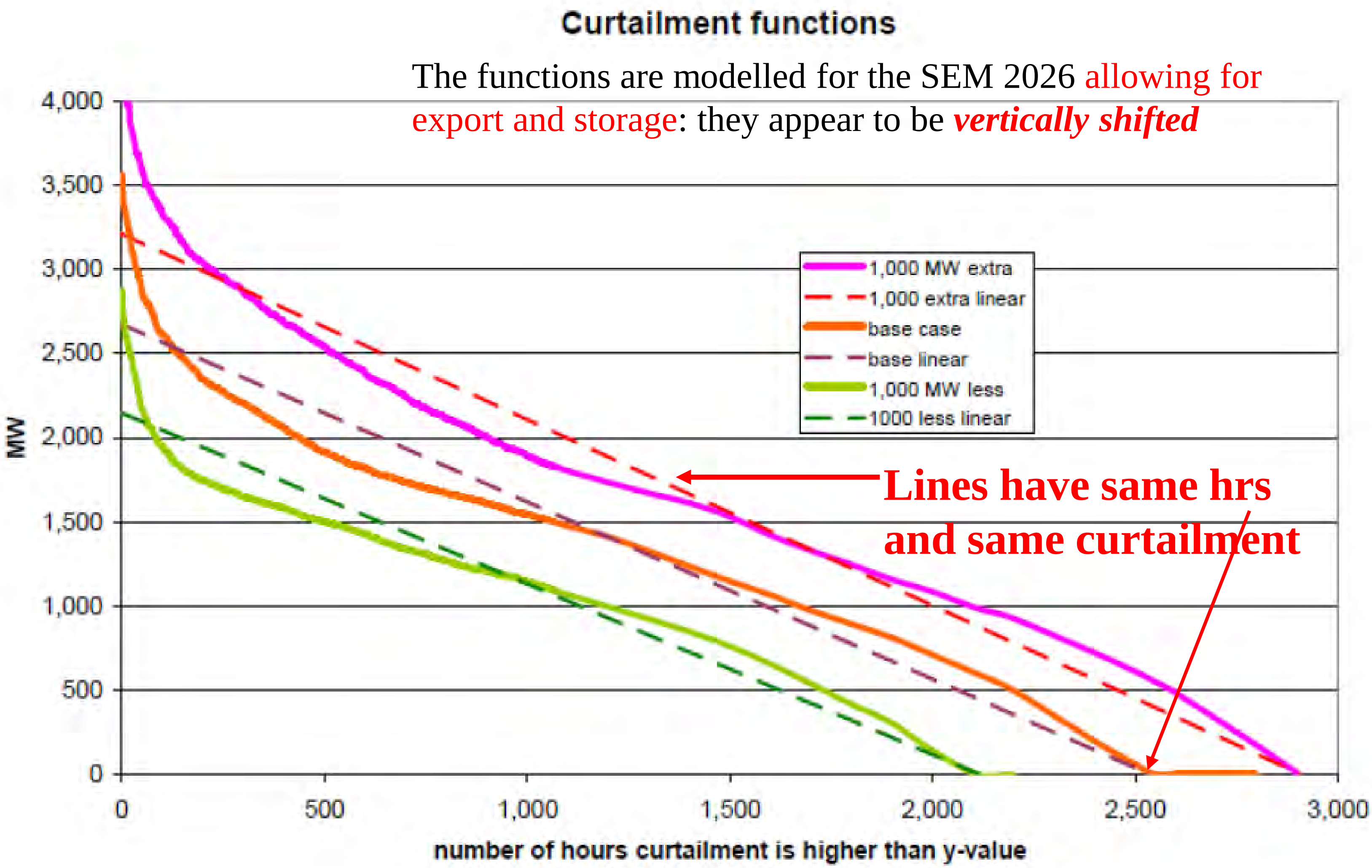
SNSP needs inertia (provided by fossil generation) in SEM



Graph 11 - DAM Executed Gas Volume against SNSP

Source: Market Monitoring Unit, SEM

Curtailment of wind in the **island of Ireland**

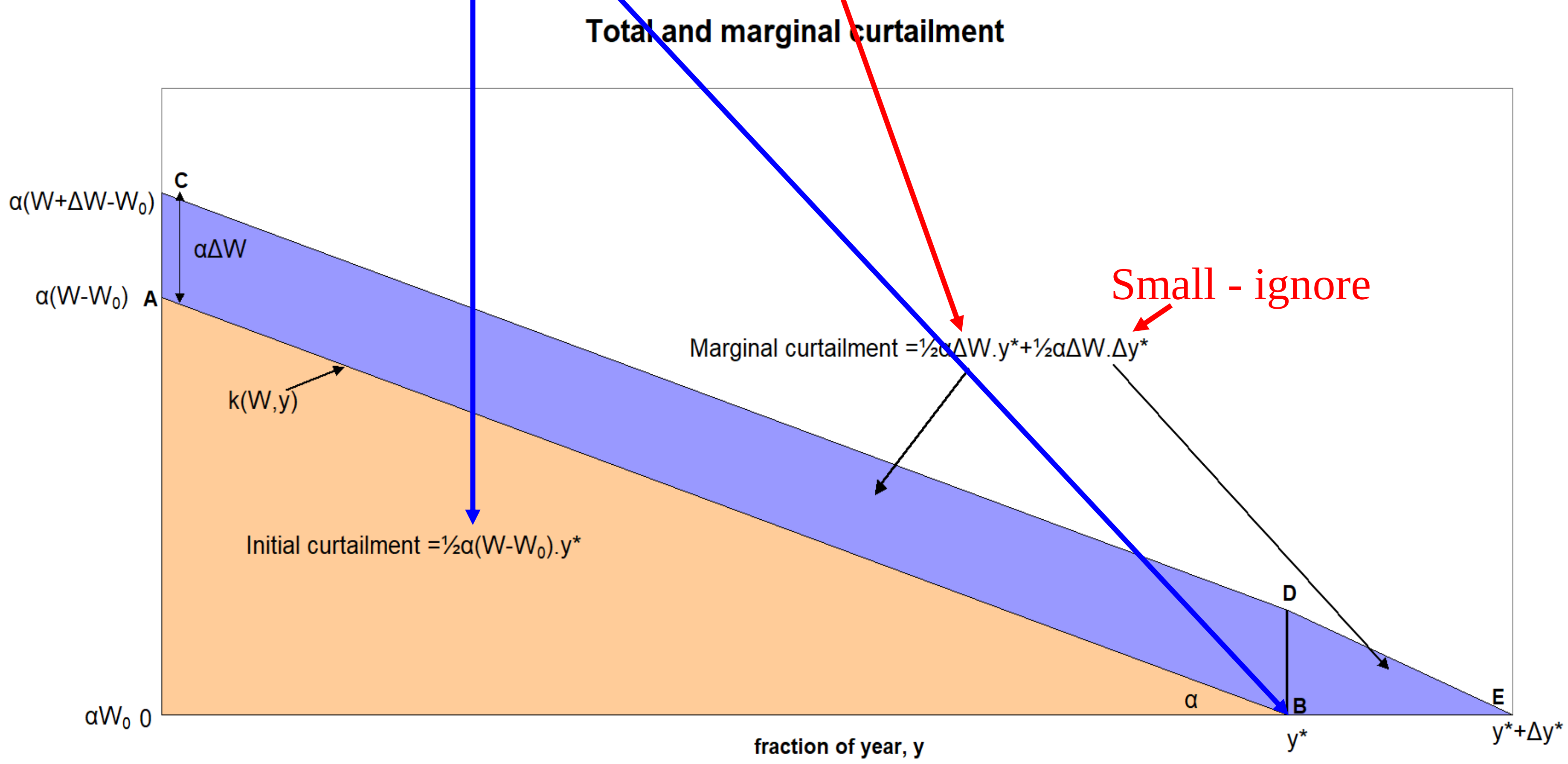


* See https://www.eprg.group.cam.ac.uk/wp-content/uploads/2020/12/2036-Text_UPD1.pdf

Ratio of *marginal to average* curtailment for simple case of parallel shifts

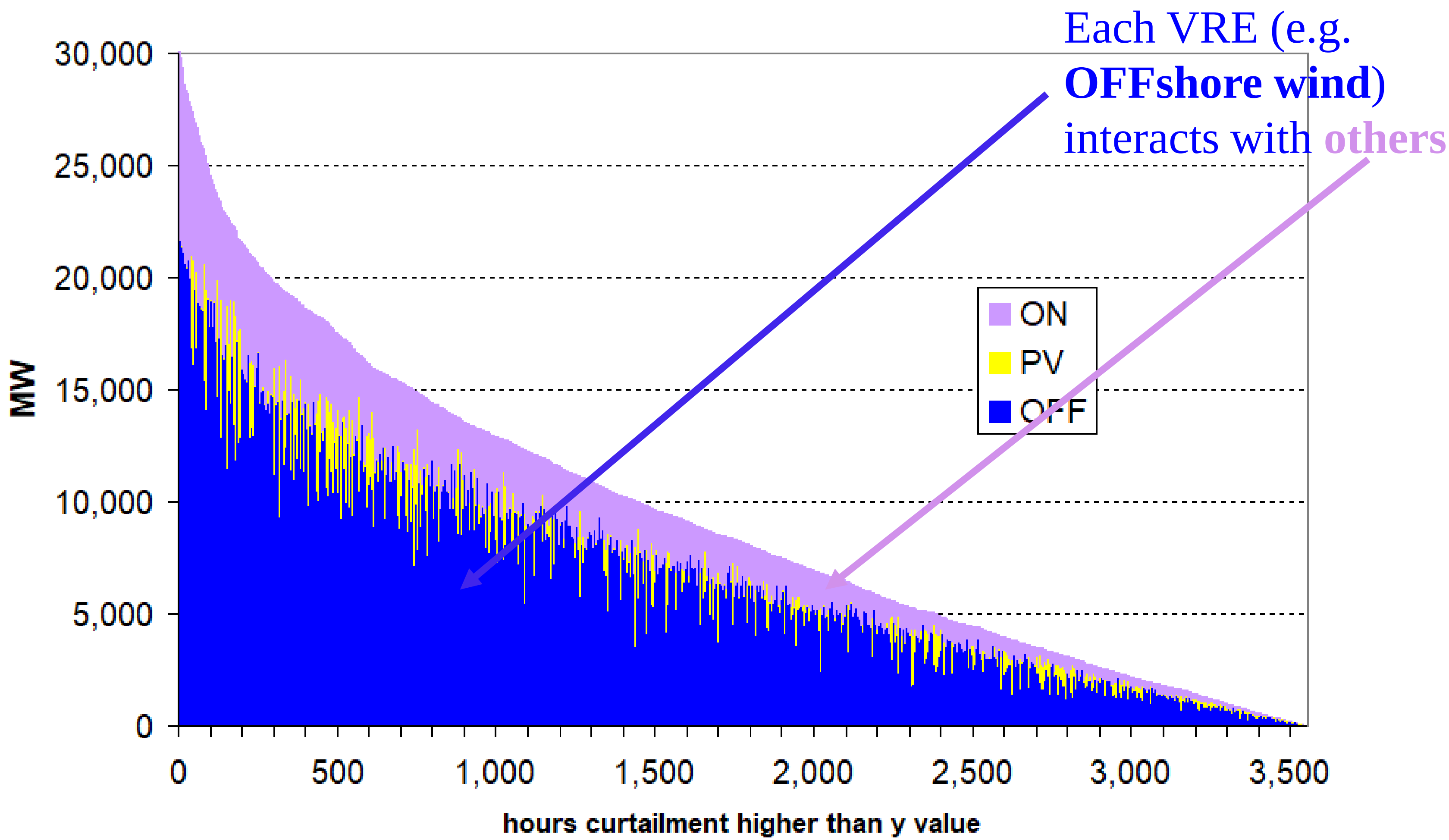
ac = ½α (W-W_0)y*/W, *mc* = ½αy*; ***mc/ac*= 2W/(W-W$_0$)**

So if W=2W$_0$ ***mc/ac*=4**.



GB 2030 *FES HE* scenario multiple VRE

GB curtailment by technology, 2030, no trade no storage



FES 2030 copper plate: no storage, no trade

	Total VRE	OFF	ON	PV	hrs
baseline cap GW	94.2	43.48	23.08	27.64	
Potential output GWh	282,073	198,854	56,935	26,284	
Potential Capacity Factor, PCF		60%	34%	11%	
baseline curtailment GWh	21,338	14,902	5,021	1,415	2,548
av. curtail, *ac*, % pot. output	7.6%	**7.5%**	8.8%	5.4%	
capacity increment MW	166.7	166.7	0	0	
Potential extra output GWh	876	876	0	0	2,584
delta curtailment GWh	**381**	275	88	18	36
***mc* p.c. of potential output**	**43.5%**	31.4%	10.0%	2.1%	
ratio *mc/ac*		5.80			
PCF/MCF		1.77			

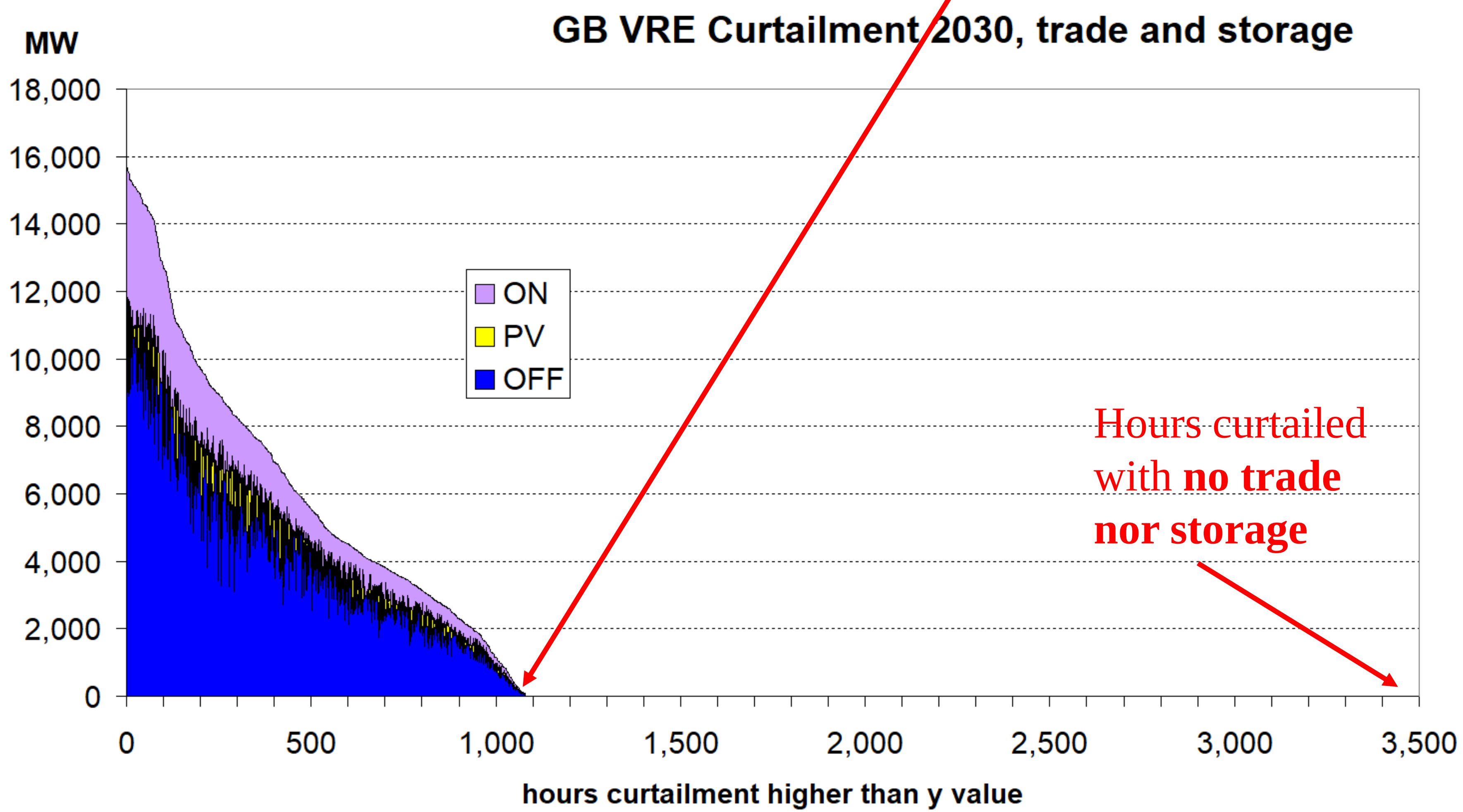
ac = 14,902/198,854

166.7 MW offshore wind = 876 GWh pot. Output ⇒ Curtailing 275 GWh OFF + 88 GWh ON + 18 GWh PV= **381** extra curtailment =381/876 = 43.5% *mc*

mc/ac = 43.5%/7.5% = 5.8

PCF/MCF = 1/(1-*mc*) = 1/(1- 43.5%) = **1.77**

Expanding interconnectors and storage **hugely decreases curtailment**



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Benefits of expanding interconnectors and storage

	Total VRE	OFF	ON	PV	hrs
Base curtail, **2023 IC+storage**	21,338	14,902	5,021	1,415	2,548
Base curtail, 2030 IC only	11,616	8,039	2,748	828	1,603
Base curtail **2030 IC & store**	8,771	6,075	2,088	608	1,341
delta curtailment of IC GWh	9,722	6,863	2,273	587	945
delta curtail storage GWh	2,845	1,964	660	220	262
ac, % of Δ potential output	3.1%	3.1%	3.7%	2.3%	
PCF/ACF = 1/(1-*ac*)	1.03	1.03	1.04	1.02	
delta curtail GWh		174	245	109	
mc VRE, % Δ potential output*		19.9%	28.0%	12.4%	
ratio *mc/ac*		6.50	7.63	5.38	
PCF/MCF		**1.25**	**1.39**	**1.14**	

ICs reduce curtailment by 46%

Storage reduces curtailment by further 24%

Much lower *acs*

Lower *mcs* but higher *mc/ac*

*876 GWh delta potential output = Av 100 MW hourly

Lower PCF/MCF = 1/(1-*mc*)

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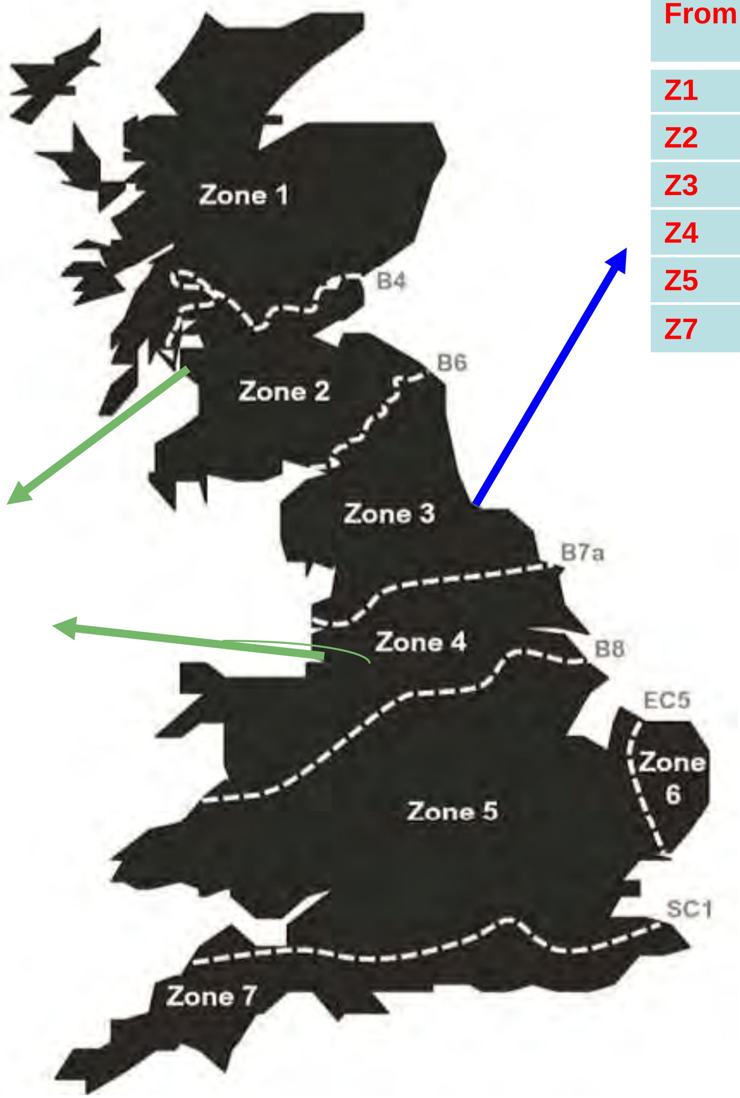
Zonal Pricing: boundaries and interconnectors in 2030

From	To	Boundary	2023 cap.	2030 cap.	External	To
Z1	Z2	B4	4,000	7,300	0	
Z2	Z3	B6	6,700	10,200	450	SEM
Z3	Z4	B7a	9,400	13,500	1,464	NO
Z4	Z5	B8	11,000	16,400	500	SEM
Z5	Z6	EC5	3,300	13,500	7,100	BE,DE, DK,NL,SEM,FR
Z7	Z5	SC1	3,900	6,100	5,000	BE,FR



Expanding VRE in one zone (Z4) impacts all other zones

Expand Z4 ON		Z1	Z2	Z3	Z4	Z5	Z6	Z7	Total
Δ curtailment	OFF	4.4	4.1	0.9	14.3	-0.7	-0.2	0.2	23
GWh	ON	7.0	6.2	0.2	1.6	-0.3	0.0	0.0	15
	PV	0.3	0.3	0.2	0.7	-0.4	0.0	0.0	1
	VRE	11.7	10.6	1.2	16.5	-1.4	-0.2	0.3	**39**
Δ pot. Output	ON				**159**				
mc p.c. of pot. output	ON				**24%**				

3% (159 GWh) potentially extra onshore wind => 39 GWh total curtailment, mostly in Scotland (Z1+Z2) and Z4

This amounts to 24% of potential output = 39/159

MCF = PCF – *mc*

LMCoE/LCoE = MCF/PCF = 1/(1-*mc*) = **1.32**

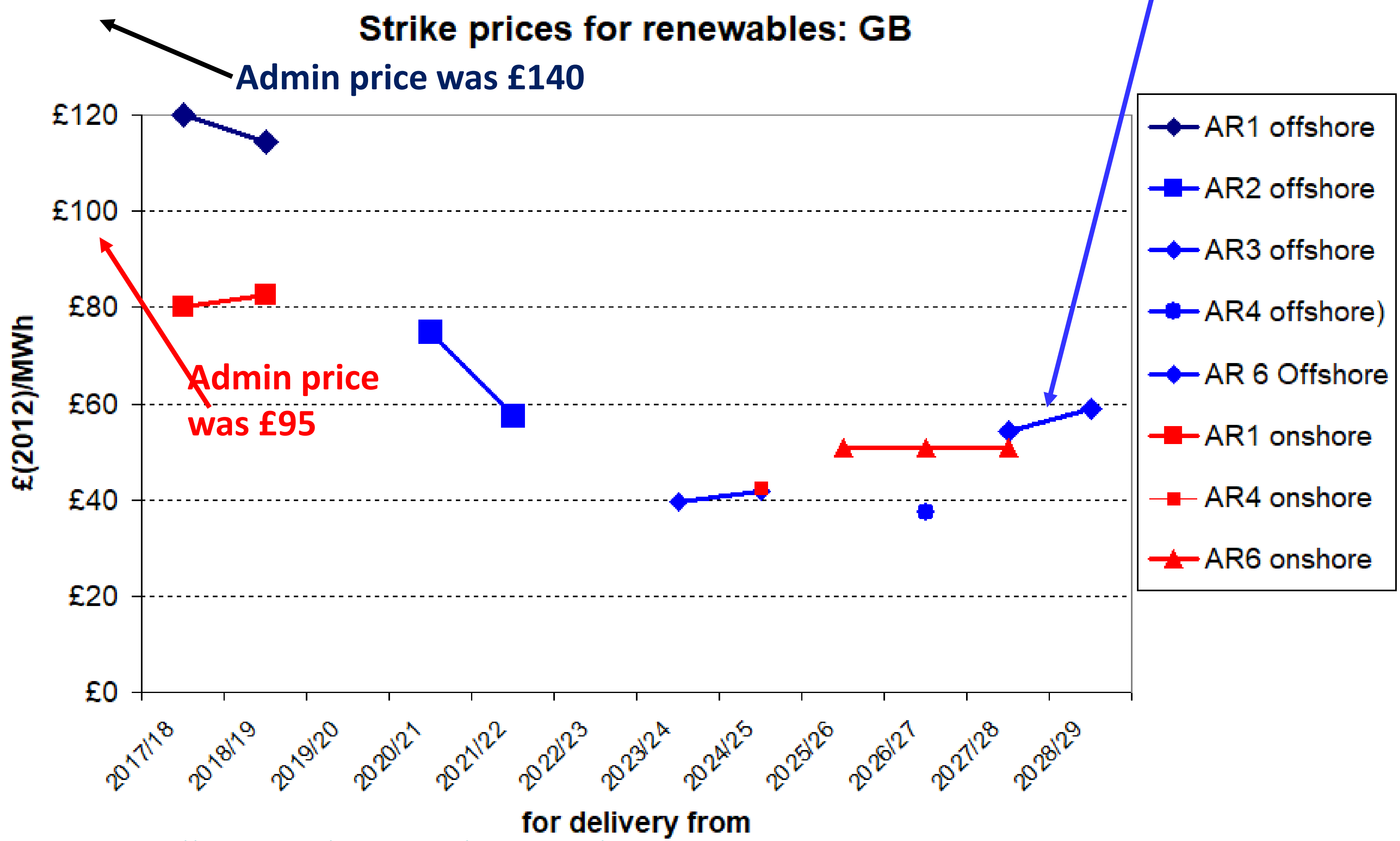
Congestion and system constraint raise long-run onshore wind costs 32%

Expand each VRE in each zone separately

		Z1	Z2	Z3	Z4	Z5	Z6	Z7	total
mc p.c. of	OFF	34%	36%	17%	17%	16%	17%	17%	20%
potential output	ON	48%	47%	21%	24%	23%	0%	14%	40%
	PV	26%	26%	12%	10%	12%	17%	10%	12%
ac p.c. pot. output	PV	8.9%	9.3%	10.3%	9.9%	10.8%	11.5%	12.0%	11%
PCF/MCF	OFF	1.52	1.56	1.21	1.21	1.19	1.20	1.20	1.25
1/(1-*mc*) = LRMC	ON	**1.91**	**1.87**	1.27	1.32	1.29	1.00	1.16	1.66
long-run marginal cost	PV	1.35	1.36	1.14	1.11	1.14	1.21	1.11	1.14
scaled for PV CF	PV	**1.67**	**1.61**	1.22	1.24	1.16	1.15	1.03	1.1

Scaled to allow for lower PV PCFs in north

Earlier auction price falls reversed



Source: https://www.gov.uk/government/publications/contracts-for-difference-cfd-allocation-round-6-results

Which levelised cost applies?

- CFD VRE auctions
  - Offered firm connection, paid on offer => **LCoE**
- If no payment when wholesale price = £0/MWh
  (Common in EU, in GB only if zero for 6+ hrs)
  - Suffer average curtailment => **LACoE**
- When considering where to allow new VRE
  - Look at LRMC = **LMCoE**

Do not invest in more Scottish VRE

EC Regulation 2024/1747

- "the energy crisis.. has revealed a number of shortcomings and unexpected consequences" (§9)
  - One-sided CfDs and Feed-in Premium => ***windfall profits***
- Public support schemes "should be two-way CfDs" (§35)
- CfDs holders "should participate efficiently in the electricity markets" (§41)

UK CfDs with FiTs meet some but not all of these

Reforming CfDs to be market responsive

Designing long-term low-risk VRE contract

- Current CfD with FiT pays fixed price for metered output
- Standard CfD: contract independent of output
  - => Generate if **price>variable cost**, not if not (buy cheaper from the market)

⇒ Make contracted amount = **forecast output**/MW of wind/PV

- ⇒ Or based on regional neighbours as in Spain

- Limit number of full operating hours to remove location distortion
  - E.g. 40,000 MWh/MW (see **(**BEIS p59 fn 31, p80 = deemed generation)
  - Provides guaranteed revenue for contract duration
- **Auction** to determine strike price for new contracts
- **Grandfather** existing contracts as location decision has been made

Conclusions

- High VRE => curtailment
  - **Inertia** needs limit VRE penetration => curtail sooner
  - **Congestion** amplifies curtailment
  - Partly mitigated by export, storage
- Single VRE (**Irish wind**) *mc/ac* = 3+
- Multiple VRE (on-, offshore wind, PV):
  - excess VRE spills over to other VRE => amplifies *mc* even if no congestion
- **Congestion** => VRE in one zone impacts other zones
  - further amplifies *mc*
  - Long-run marginal cost proportional to **1/(1-*mc*)**

Expanding VRE in Scotland very costly

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Acronyms

a(m)c:	average (marginal) curtailment (% potential output curtailed)
A(M)C:	Average (marginal) capacity factor
CfD:	Contract for Difference
FES:	Future Energy Scenario (of National Grid)
FiT:	Feed-in Tariff (paid on metered injection)
L(A,M)CoE:	Levelised (average, marginal) cost of electricity
LRMC:	Long-run marginal cost
OFF:	Offshore wind
ON:	Onshore wind
PCF	Potential Capacity Factor
PV	Solar photovoltaic
VRE:	variable renewable electricity

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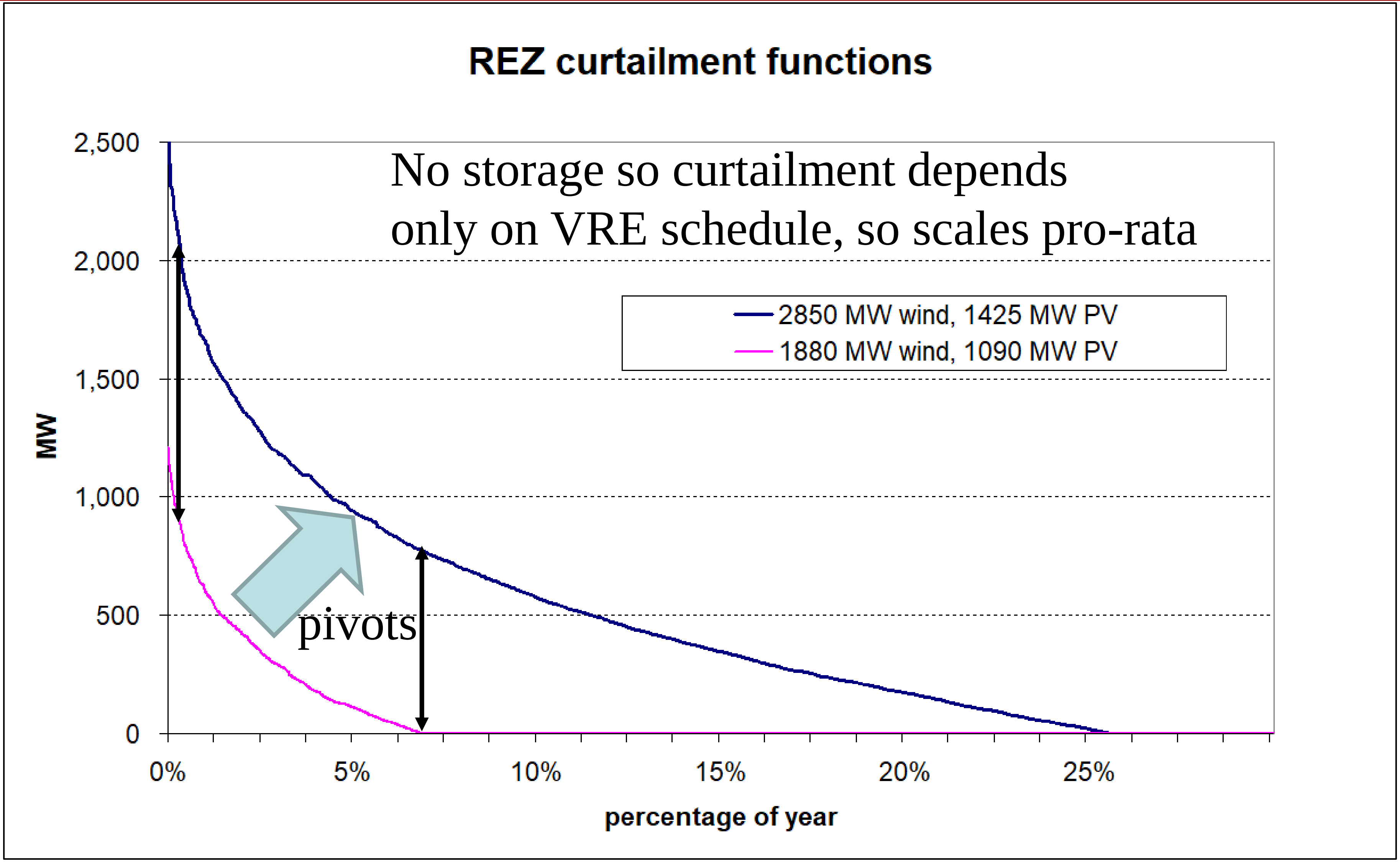
Steps to find curtailment for single VRE (wind in SEM)

1. Can SEM export? (are neighbours in surplus?)
2. If not, SNSP 85% of demand limits wind for consumption
   – If still surplus, put into storage until full
3. Remainder is spilled wind to be curtailed
4. Rank curtailed MWh in descending order to zero
5. Total = curtailment
6. Increase capacity by 100 MW, re-estimate curtailment

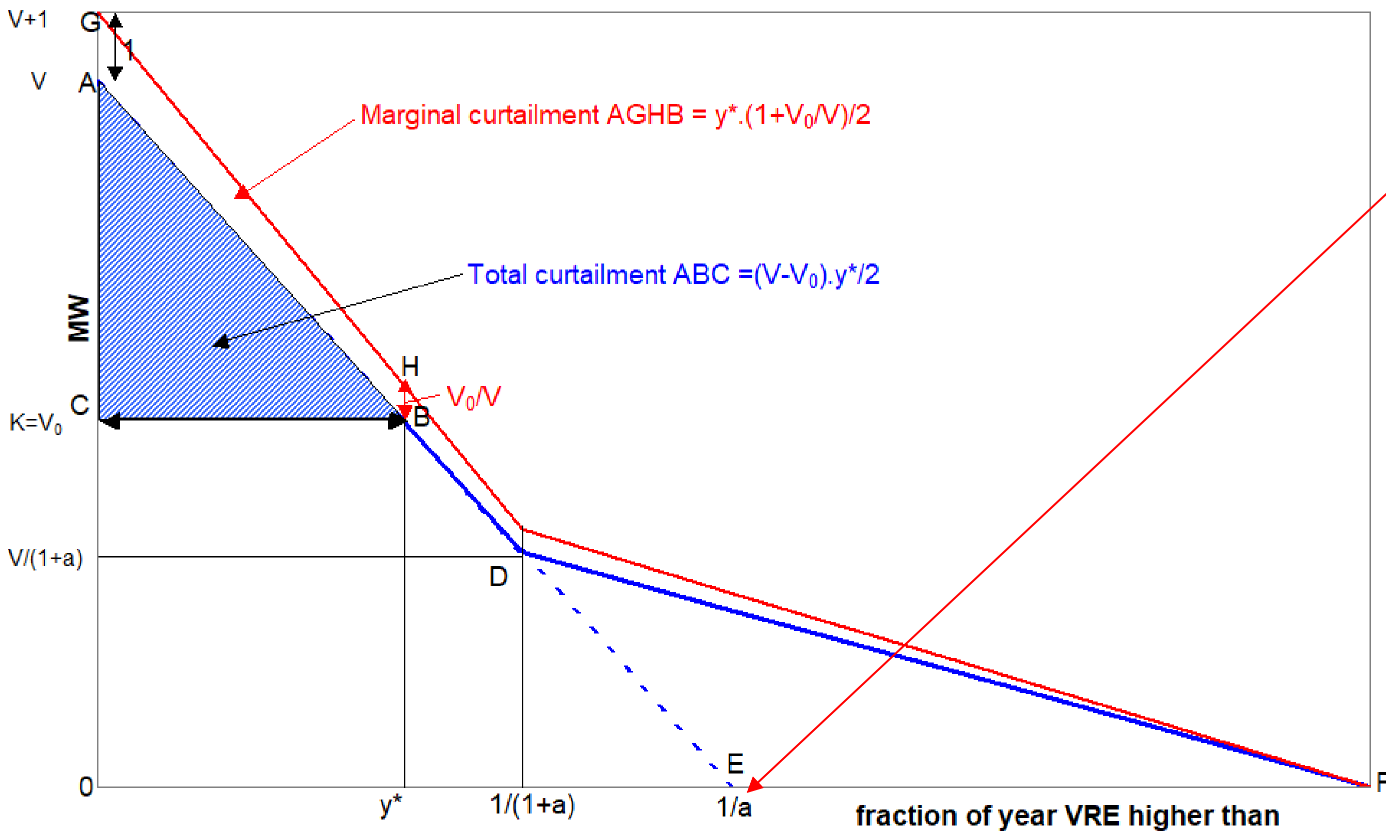
=> *Marginal curtailment* = per MW extra wind

= **3-4 times** average curtailment

Queensland REZ example: scaling VRE => *scaled* curtailment



Geometry of marginal and average curtailment



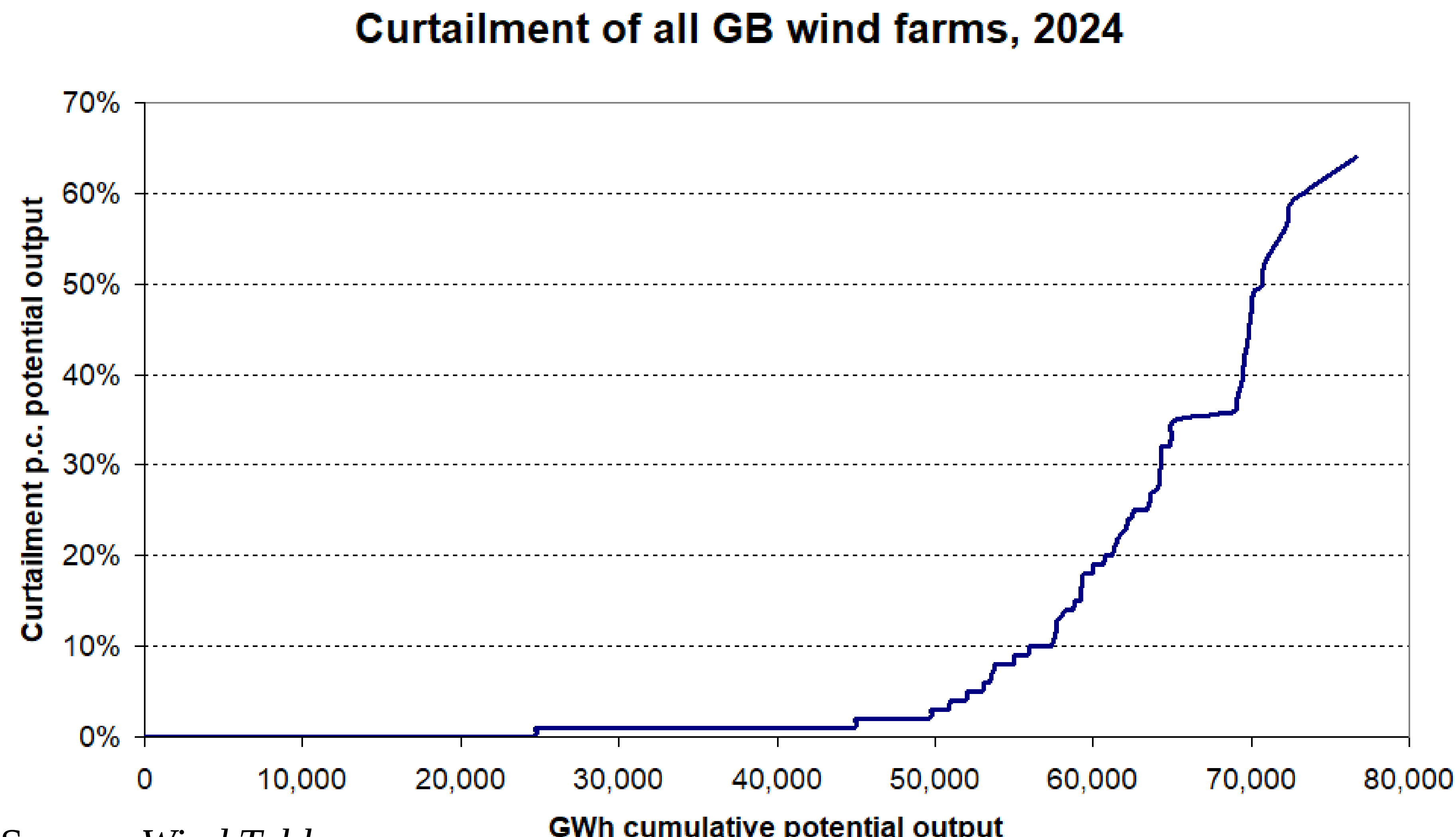
If **a** = 2,

peak:average=3

MC= ½ y*(1+V_0/V); AC = ½ (V-V_0)y*/V,

MC/AC= (V+V_0)/(V-V_0) So if V=2V_0 **MC/AC=3**.

High levels of *average* curtailment



Source: *Wind Table*

Cumulative excess subsidy from a time-based contract

Subsidy calculated from rolling capacity factors
Auction clears at 25% CF and £50/MWh subsidy for 15yr contract