

Club Goods and a ‘Tragedy of the Commons’

Renewable energy: learning and curtailment

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**FINANCING LONG-TERM INVESTMENT IN HYBRID
ELECTRICITY MARKETS**

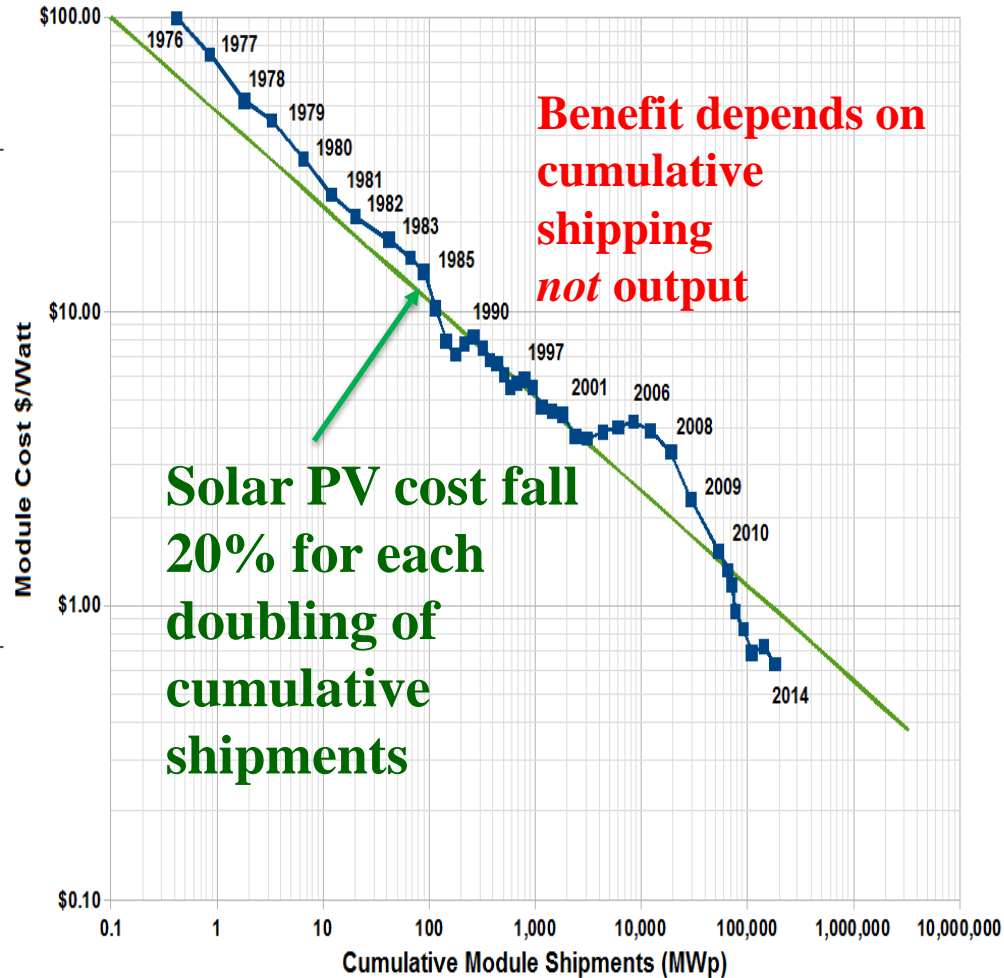
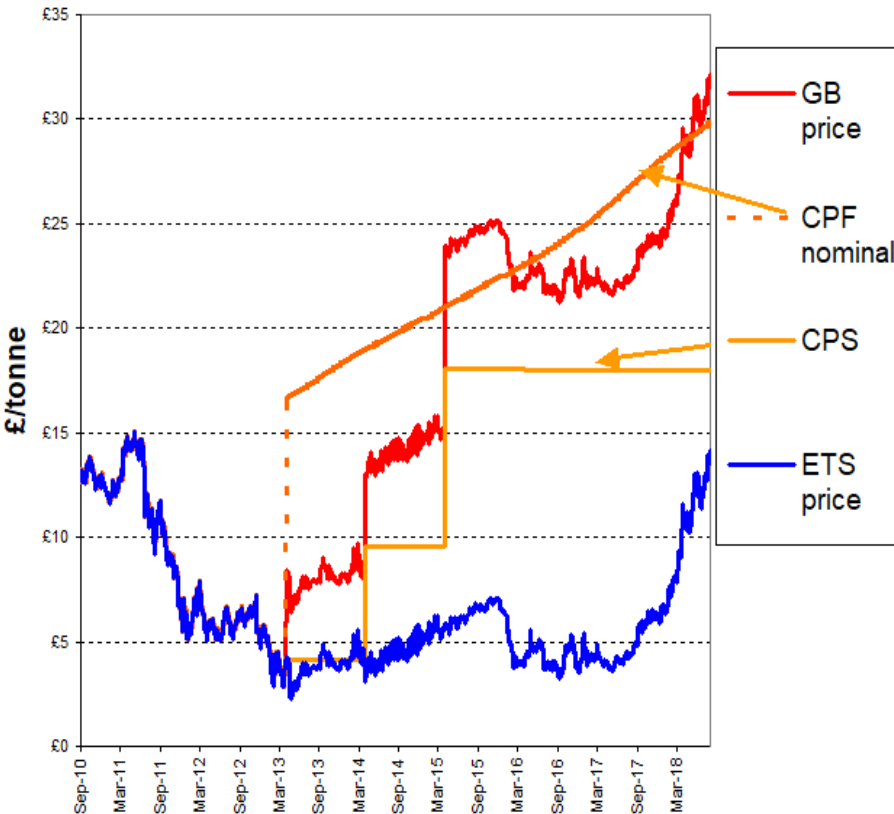
CEEM Dauphine

22nd June 2021

- **EU Clean Energy Package** is a Club Good
 - Club membership finances public goods
 - carbon prices charge for global climate damage
 - renewables support finances learning-by-doing spill-overs
 - *National Energy and Climate Plans*
 - => high wind/PV variable penetration by 2025-30
- **Tragedy of the commons**
 - Common resources risk over-exploitation
 - Wind curtailment forces price to near zero
 - **Marginal curtailment** of an extra 1 MW wind = 3-4x average
 - Last entrant enjoys **average not marginal curtailment**
- **Island of Ireland** at forefront of high wind penetration
 - => **model SEM to quantify these failures**

Address external costs (CO₂) and learning benefits

EUA price now €50/tonne
ETS and GB CO₂ prices, 2011-18

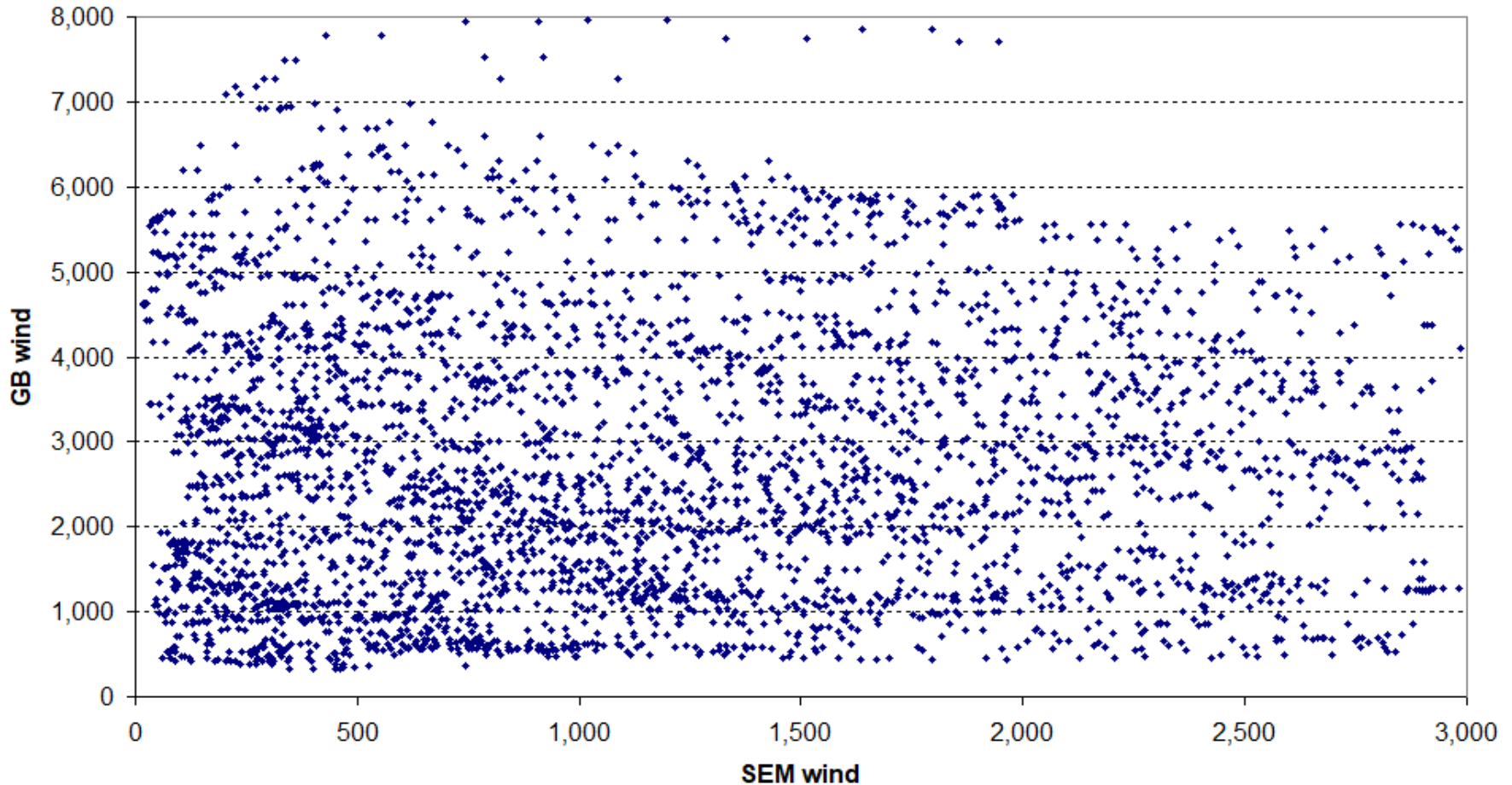


- **EU ETS prices CO₂**
 - **Stiglitz Report:** Paris target-consistent price at least **US\$40–80/tCO₂** by 2020 and US\$50–100/tCO₂ by 2030
 - June 2021 **EUA price €50/t CO₂ = \$60/t CO₂**
 - **Renewables targets => implicit subsidy for learning externalities**
 - **Installation => learning cost reduction => no subsidy to output**
 - E.g. for on-shore wind by mid 2020's **global learning externality** could be **10%** of capital cost
- ⇒ [MISSION INNOVATION](#) *agrees **global learning subsidies***
Accelerating the Clean Energy Revolution

- Island of Ireland submits *National Energy and Climate Plans (NCEP)*
 - Single Electricity Market (SEM) target: **55% wind** by 2026
 - Almost all **on-shore**, little PV, Celtic Link not due before 2026
 - **GB, FR, BE, NL, DE, ES** published **NCEPs**
 - Can forecast implied wind, solar, nuclear (surplus=>zero price)
- ⇒ if **total area** in surplus; SEM cannot export surplus wind
- ⇒ Reduces value of extra interconnectors

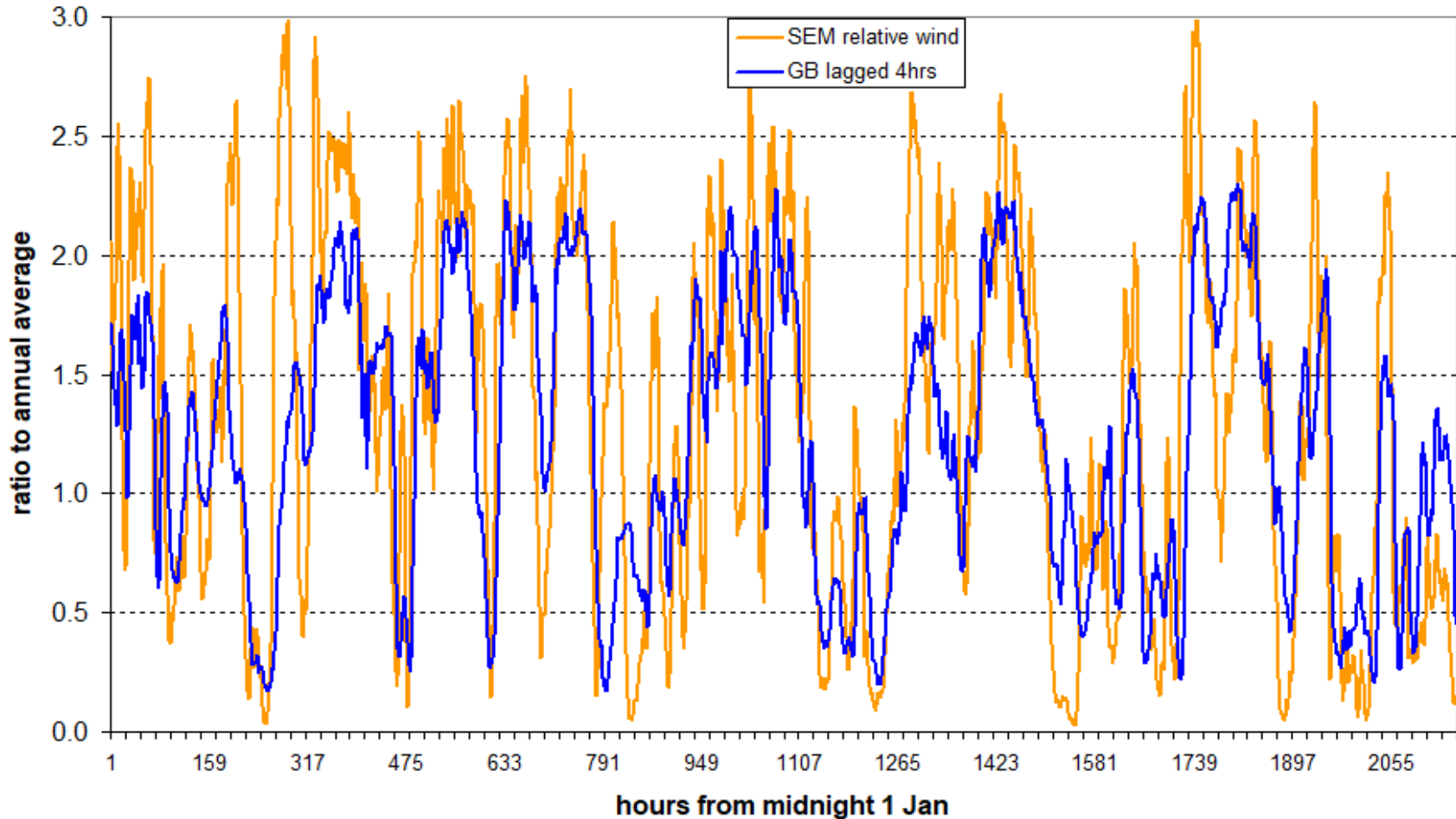
SEM wind *appears* uncorrelated with GB wind – **interconnection good?**

Hourly GB wind vs SEM wind Nov 2016-March 2017

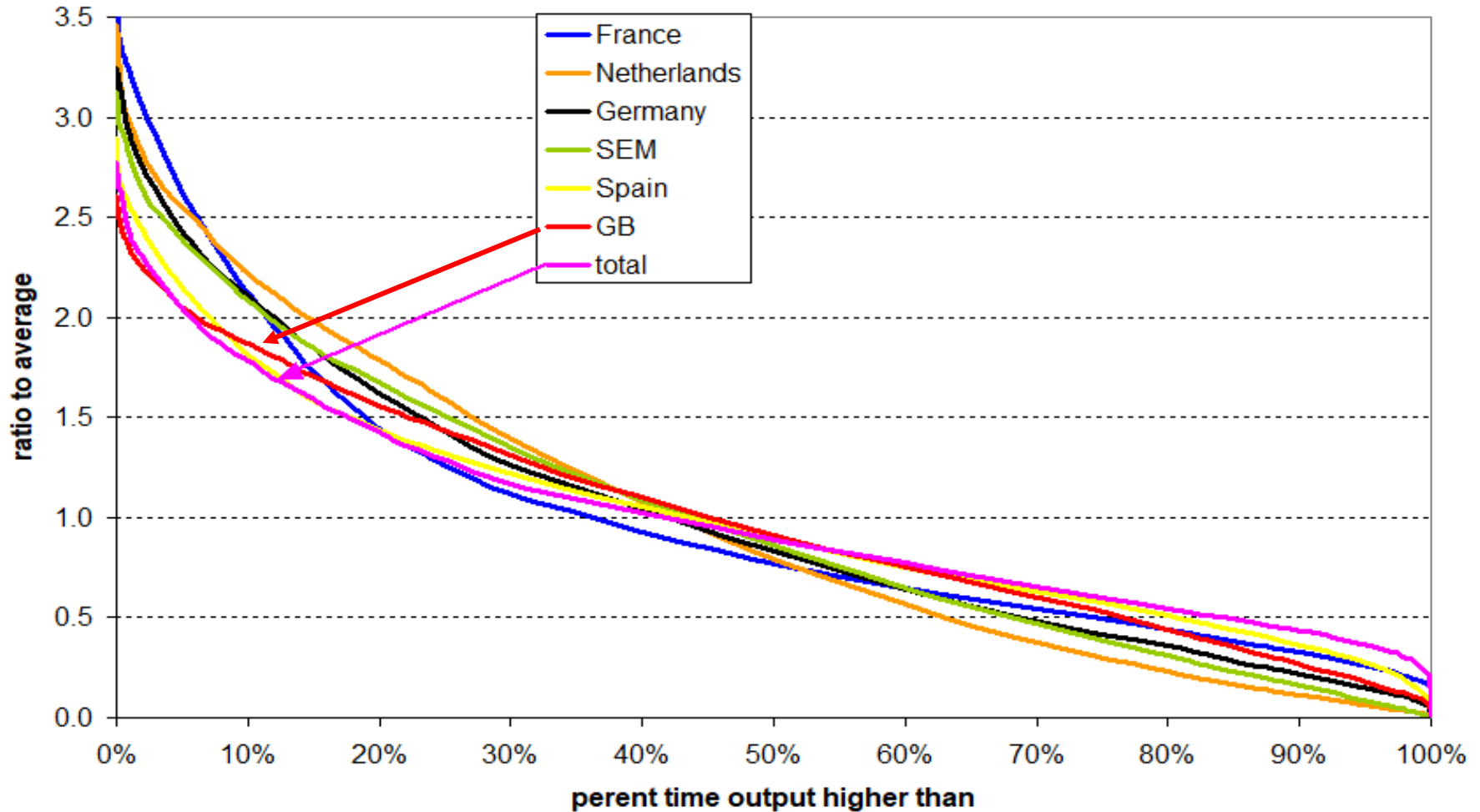


But GB follows SEM wind with **4-hr lag => need temporal model**

SEM and 4-hr lagged GB relative wind Jan-March 2018



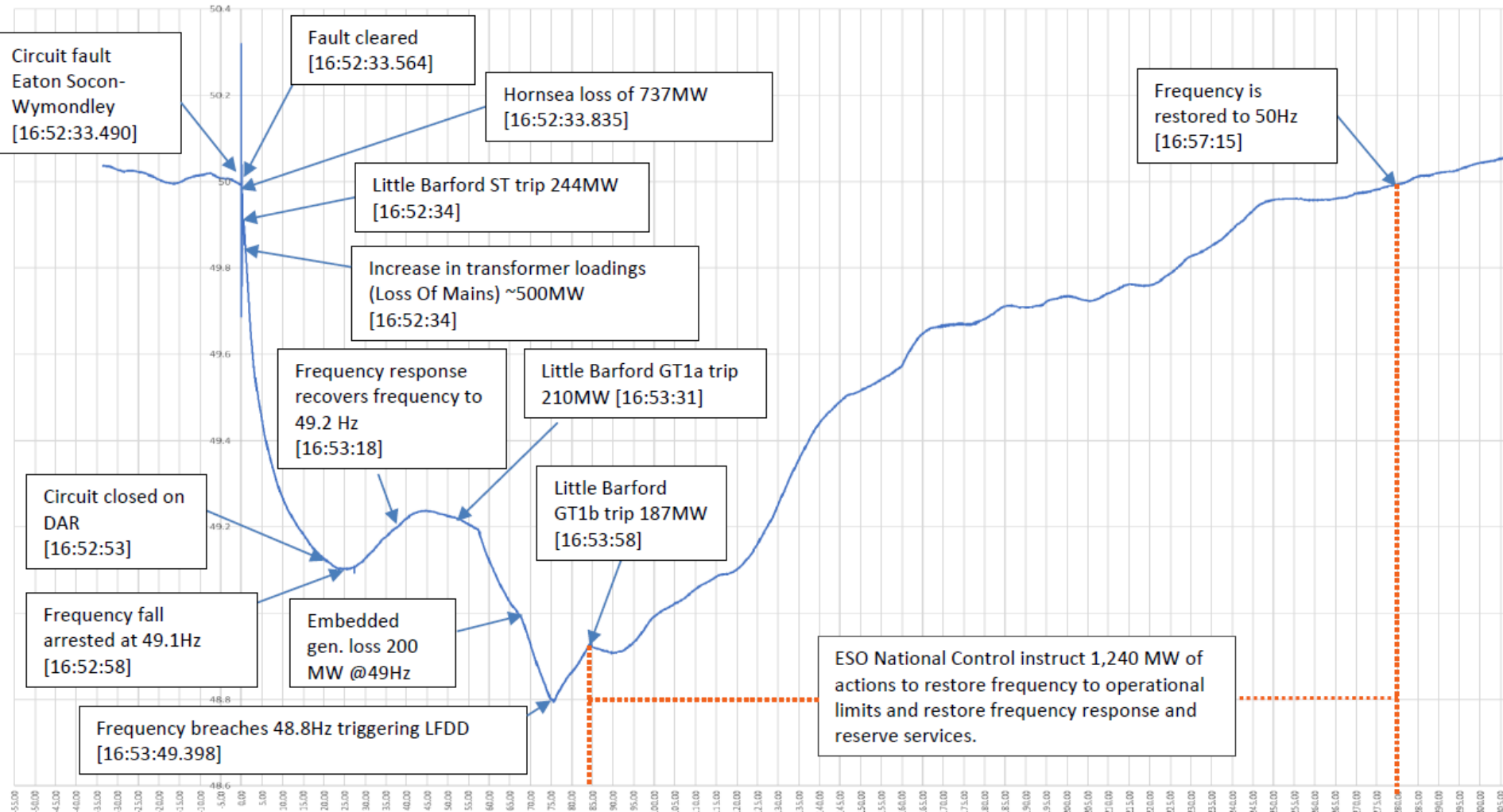
Comparison of relative wind duration curves 2017



- Five units have to be running for **stability**
 - Minimum stable generation (MSG) = 795 MW
 - N-1 constraint – spinning reserves = largest single infeed
 - Satisfied by MSG
 - Simultaneous Non-Synchronous Penetration, **SNSP** < 75% (2020)
 - Wind, PV, DC interconnectors are non-synchronous: **cannot provide inertia**
 - Inertia reduces the rate of change of frequency (ROCOF): time to lower frequency limit
 - Breaching ROCOF limits **risks disconnecting more generation**
 - SEM is in process of raising ROCOF to 1 Herz/sec (GB currently at 0.25Hz/sec)
- => Consider ambitious target of 85% SNSP**
- Cannot export surplus if neighbours saturated
 - Consider **storage**:
 - PSP can take 292 MW for 8 hrs, BES 500 MW for 1 hr
 - EVs in 2026 670 MW up to 1 GWh **if enabled**
 - Immersion heaters – conceivably up to 3.8 GW up to 1.9 GWh **if enabled**

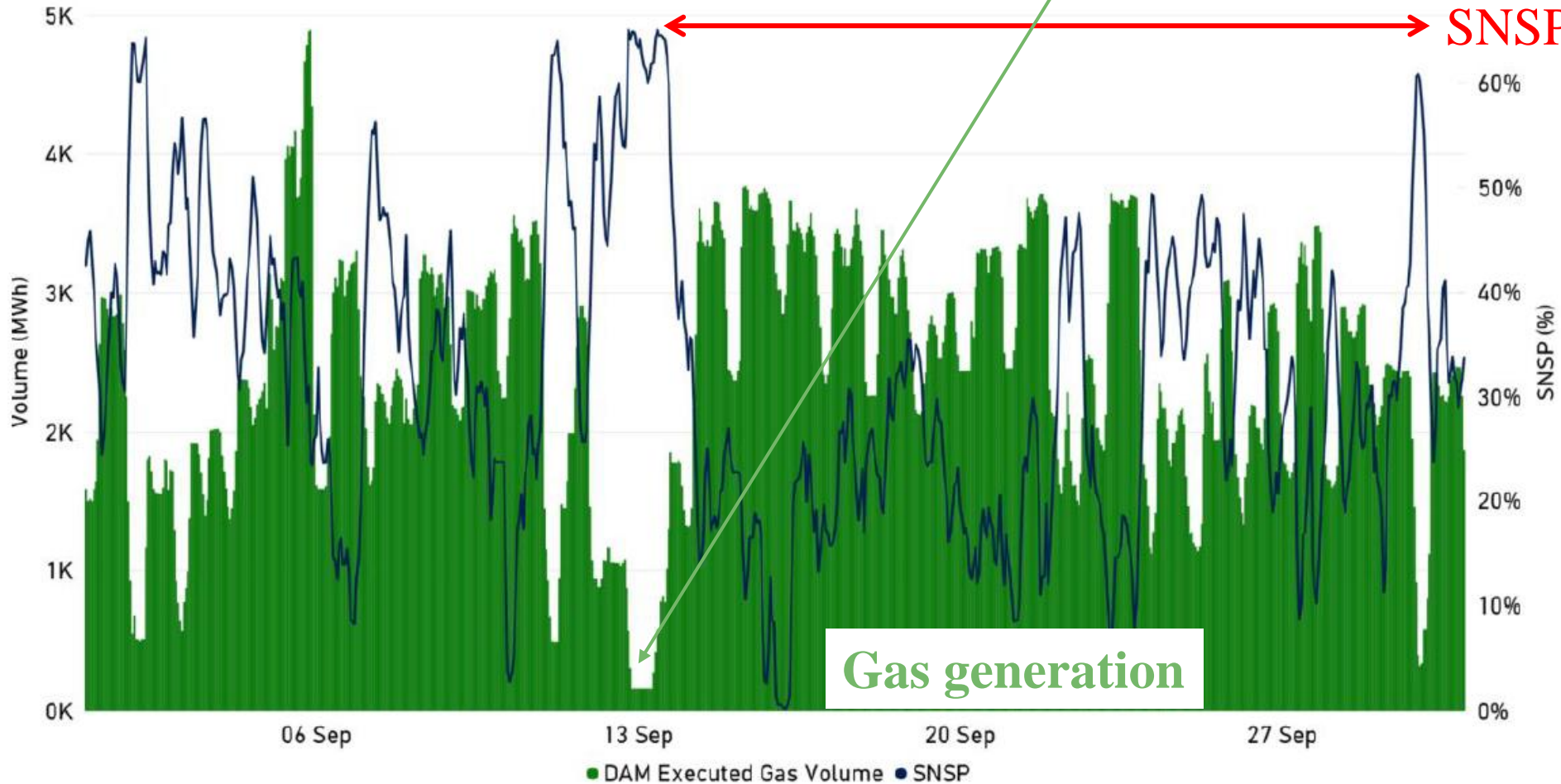


Frequency evolution in GB in Aug 2019 blackout





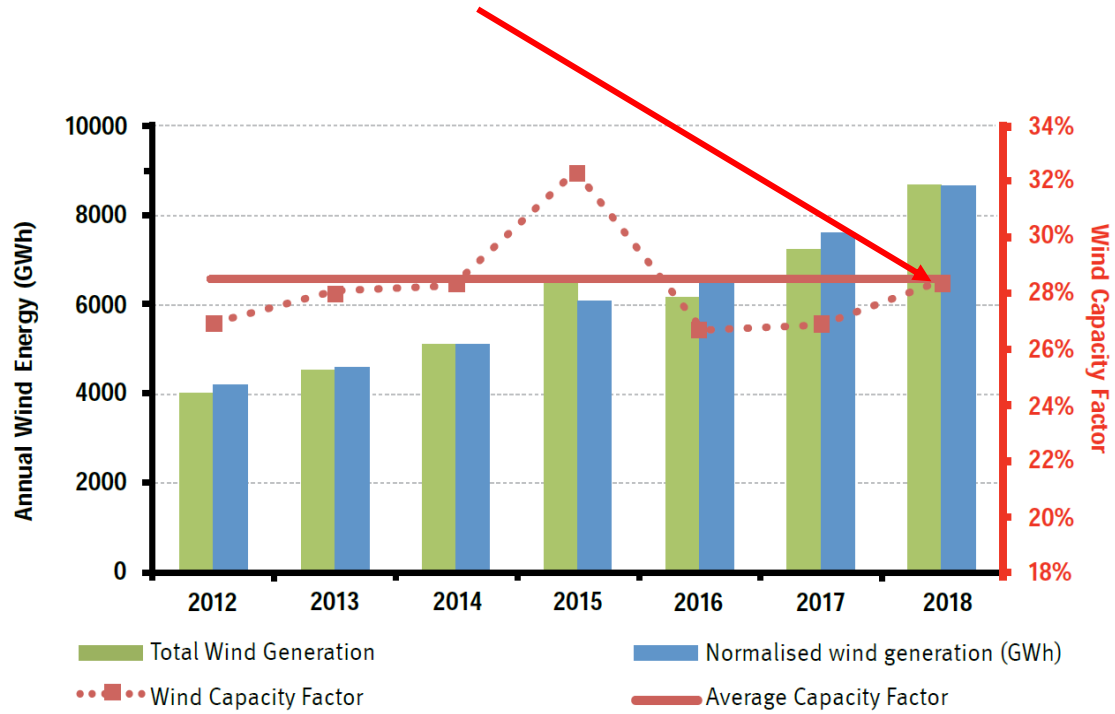
SNSP needs fossil generation



Graph 11 - DAM Executed Gas Volume against SNSP

Source: Market Monitoring Unit, SEM

- Scale 2018 hourly demand by 1.25 for 2026 45.5 TWh
- 55% wind is 26.2 TWh
- **2018 is an average wind year, 28.4% capacity factor**
 - **Scale up 2018 hourly wind by 2.18 to meet target**

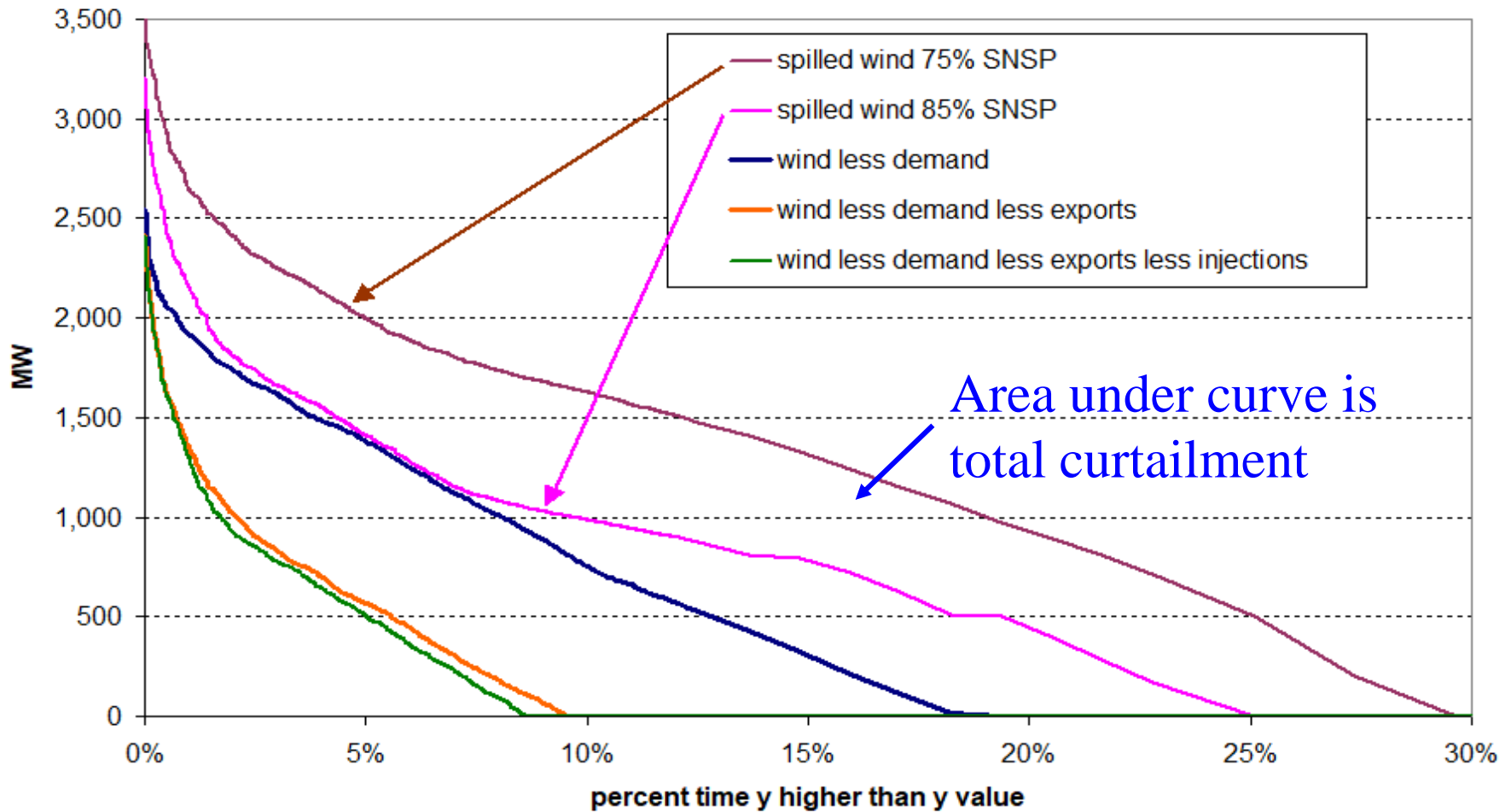


Source: Eirgrid (2019)

Figure 20 - The actual and normalised annual energy produced from wind power in Ireland over the last six years. In red are the figures for annual wind capacity factor, and their average

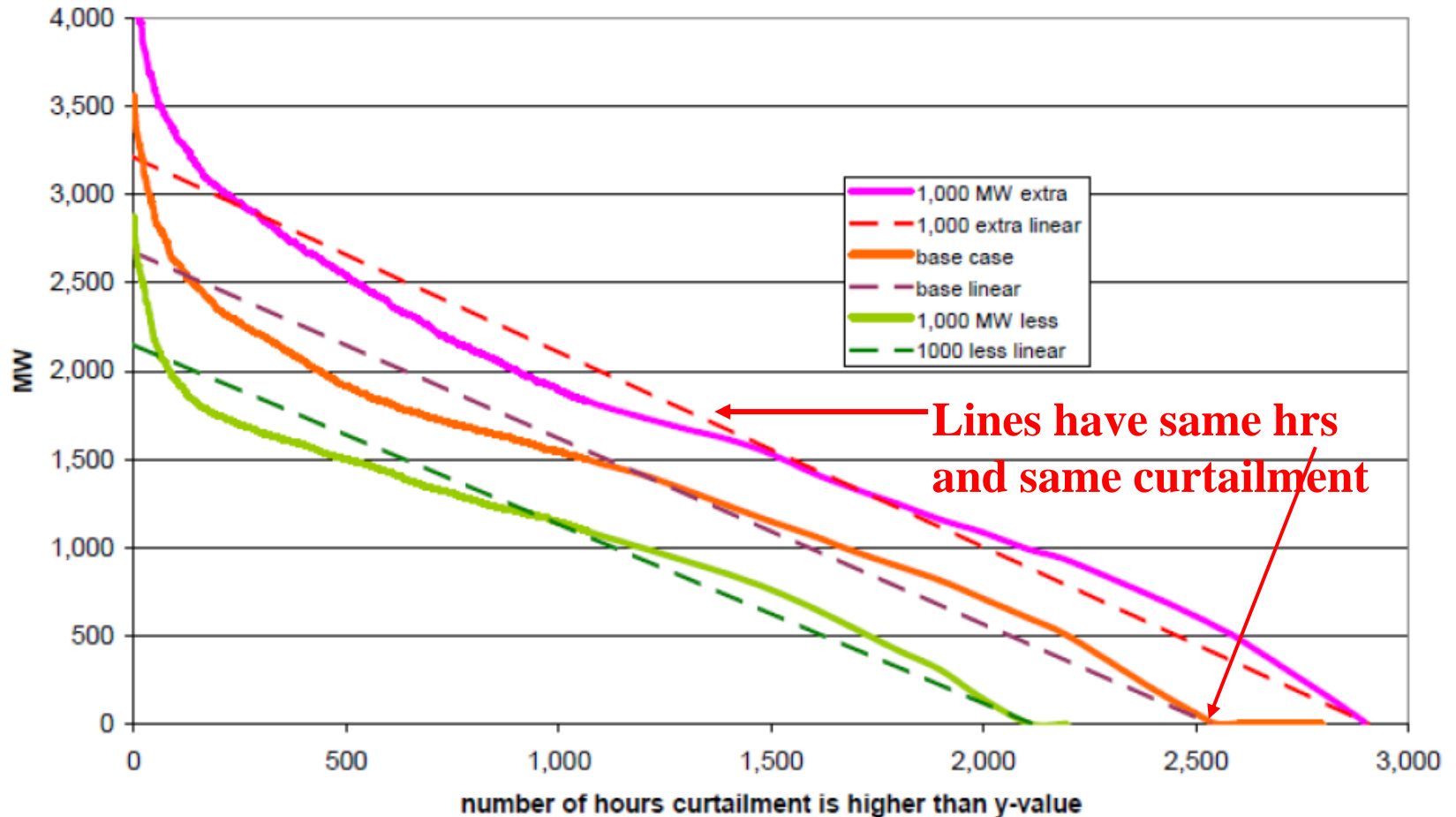
1. Can SEM export? (are neighbours in surplus?)
 2. If not, SNSP 85% of demand limits wind for consumption
 - If still surplus, put into storage until full
 3. **Remainder is spilled wind to be curtailed**
 4. Rank curtailed MWh in descending order to zero
 5. Total = curtailment
 6. Increase capacity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

Illustrative duration curves for SEM 2026



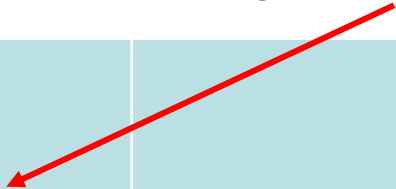
Linearizing allows simple algebraic curtailment model

Curtailment functions





Increasing **SNSP** has large impact



SNSP	Curtail GWh	percent	Delta GWh
75%	3,388	13.3%	
80%	2,642	10.4%	746
85%	2,050	8.1%	592
90%	1,826	7.2%	224

Storage remarkable ineffective at storing surplus wind

Impact of increasing BES, (SNSP=85%), GWh/yr

Extra MW BES	Curtail GWh/yr		Delta GWh
0	2,042	8.0%	
100	2,023	8.0%	18.47
200	2,006	7.9%	17.85

Less than 3% of potential storage capacity

Effect of halving storage capacity (SNSP=85%) GWh/yr

SNSP	GWh/yr	percent	delta	rel to full storage
75%	3,536	13.9%		148
80%	2,784	10.9%	753	141
85%	2,187	8.6%	597	137
90%	1,961	7.7%	225	136

1. Cost of fossil capacity to meet reliability standard, $C_f(W)$
2. Differentiate w.r.t $W = \text{cost saving}$ from 1 MW extra wind.
3. Social value of 1 MW wind, S_W , is

$$S_W = -\partial C_f / \partial W - (r_W + v_W(H - h^*)\phi_e).$$

where the $(-)$ is the annual fixed cost, r_W , of 1 MW wind, v_W is the unit variable cost, ϕ_e is the effective capacity factor over the uncurtailed hours, $H-h^*$.

3. Find the market surplus (revenue less cost) M_W
4. Find **corrective charge**

$$\tau = M_W - S_W.$$

- Renewables are de-rated to estimate their contribution to reliability – e.g. wind in SEM at 10%
 - But wind (& PV) best treated as one **very large turbine**
 - **Highly correlated output, not independent** generators
- => care needed in setting de-rating factor
- Market rewards **average not worst case scarcity**
- => **tragedy of commons**: competitive market prices set by **average** curtailment but value depends on **margin**

The **corrective charge** has two components

$$\tau(W) = \underbrace{r_P(E\lambda\phi_\lambda/L - \delta_W)}_{\text{excess capacity credit}} + (v_p - v_W)E\lambda\phi_\lambda + \underbrace{v_F\beta\phi_{H-h^*}W \frac{\partial h^*}{\partial W}}_{\text{marginal curtailment}} > 0$$

choose δ_W to make zero

r_P = fixed cost of peaker, L is reliability target (8hrs), λ actual stress hrs

$E\lambda\phi_\lambda$ Expected wind output in these hours, δ_W = derating factor,

$(v_p - v_W)E\lambda\phi_\lambda$ extra operating costs then (tiny)

$\beta = (1 - \text{SNSP})$ - fraction met by synchronous plant for frequency stability,

ϕ_{H-h^*} = wind capacity factor at the curtailment margin,

v_F = baseload fossil variable cost

$\frac{\partial h^*}{\partial W}$ = marginal curtailment, hrs/MW; W = wind capacity,

- Learning externality => capacity **subsidy** to fixed cost of wind, **central estimate is 10% of fixed cost** in 2026 (7%-16%)
- Set de-rating δ_w so first component = zero
- **Curtailement cost** (SNSP = 75%, no Celtic Link) is **20%**
- Ambitious scenario (85% SNSP, Celtic Link, 3 x storage): cost is **10%**

Conclusion –offset each other in ambitious scenario if capacity de-rating is corrected

- Decentralise => subsidize wind for **learning externalities** but impose **corrective entry charge** in annual grid charge
- Decentralise but ignore both as they are modest and offsetting
- Or set target (e.g. 55%) and **auction for capacity subsidy**
 - Additional payment for first 30,000 full operating hours (MWh/MW) – see Newbery (2021)

- High wind penetration on island leads to **curtailment (8-13%)** but **marginal curtailment 4 times** as high
- Interconnection helps, **raising SNSP more** so, storage less
- De-rating of wind understates average wind revenues in stress hours (based on worst case events), so market **over-rewards wind capacity, needs correction**
- Marginal curtailment determines social value but revenue depends on average curtailment, so need **corrective entry cost** (annual fixed charge) **to induce efficient entry**
 - But counterbalanced by **learning externality**
- **Or** auction for wind €X/MWh for 30,000 full hrs (MWh/MW)

- Government of Ireland, *2019 Climate Action Plan 2019*, at https://www.dccae.gov.ie/en-ie/climate-action/publications/Documents/16/Climate_Action_Plan_2019.pdf
- Newbery, D., 2020. Club goods and a tragedy of the commons: the Clean Energy Package and wind curtailment, at <https://www.eprg.group.cam.ac.uk/eprg-working-paper-2036/>
- Newbery, D., 2020. Implications of the *National Energy and Climate Plans* for the Single Electricity Market of the island of Ireland, EPRG WP 2020 at <https://www.eprg.group.cam.ac.uk/eprg-working-paper-2020/>
- Newbery, D., 2021. Designing efficient Renewable Electricity Support Schemes, at <https://www.eprg.group.cam.ac.uk/eprg-working-paper-2107/>
- World Bank, 2019. *Report of the High-Level Commission on Carbon Pricing and Competitiveness*. Carbon Pricing Leadership Coalition, World Bank, Washington, DC. © World Bank. <https://openknowledge.worldbank.org/handle/10986/32419> License: CC BY-NC-ND 3.0 IGO.



Spare slides

Impact of **700 MW Celtic Link** at varying SNSP on curtailment

SNSP	curtail GWh/yr	percent	saved by Celtic Link, GWh
75%	3,153.7	12.4%	235
80%	2,392.3	9.4%	250
85%	1,775.1	7.0%	275
90%	1,515.4	6.0%	310

Comparing value of **900 MW current interconnection** for 2026

SNSP	curtailed GWh/yr	percent	saved by current IC GWh
75%	4,085.0	16.1%	697
80%	3,393.3	13.3%	751
85%	2,907.2	11.4%	858
90%	2,752.8	10.8%	927

Let F be fossil capacity, W wind capacity, $D(h)$ is demand duration schedule, L is Loss of Load Expectation, δ de-rating factor, then

$$F\delta_F = D(L) - W\delta_W, \text{ so}$$

$$\frac{\partial F}{\partial W} = -\frac{\delta_W}{\delta_F}.$$

$k(h, W)$ is curtailment function, h^* hours curtailed when

$$k(h^*, W) = 0,$$

$$k = A(1 - h(\theta)/h_r^*) + \alpha(\theta W - W_r)$$

Average curtailment with capacity factor ϕ and H hrs/yr

$$\frac{\int_0^{h^*} k(W, h) dh}{W\phi H}$$

Calibrating to SNS = 75%

$$\int_0^{h^*} k(W, h) dh = \frac{1}{2} Ah_r^* = 3,388 \text{ GWh},$$

Marginal curtailment is

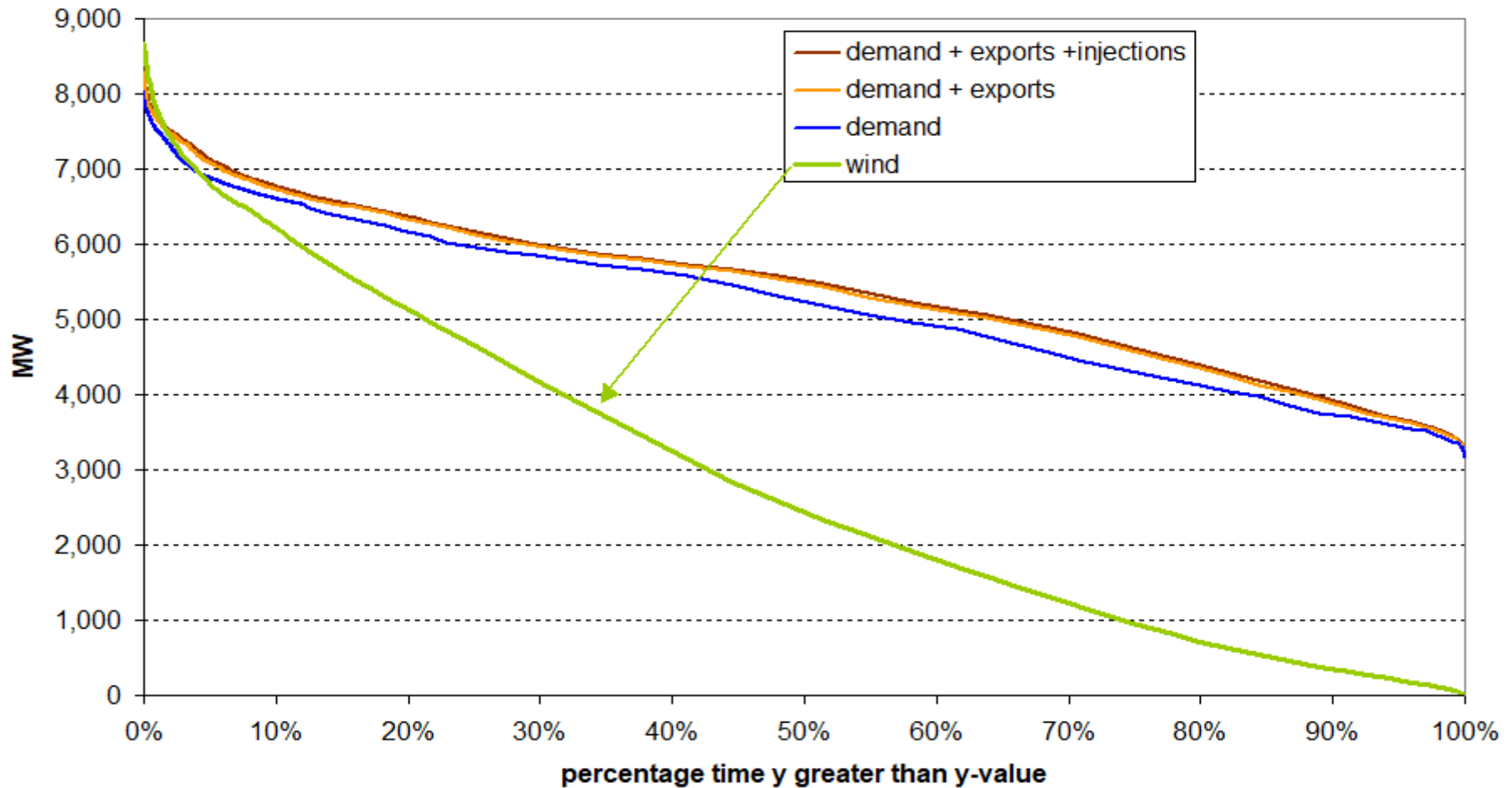
$$\int_0^{h_r^*} \frac{\partial k}{\partial W} dh = \int_0^{h_r^*} \alpha dh = \alpha h_r^* = 1,213 \text{ MWh/MW}.$$

**Ratio to average is
or roughly 4:1**
(consistent with
simulation)

$$\frac{W_r \int_0^{h_r^*} \frac{\partial k}{\partial W} dh}{\int_0^{h^*} k(W, h) dh} = \frac{2\alpha W_r}{A} :$$

Duration curves: *each ranked separately*

Illustrative duration curves SEM 2026



EUA: EU Allowance (to emit 1 tonne CO₂)

NCEP: National Energy and Climate Plan

SNSP: System non-synchronous penetration (= share of wind and PV)