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Club Goods and a 'Tragedy of the Commons'

Renewable energy: learning and curtailment

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IAEE Webinar

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Outline

- **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

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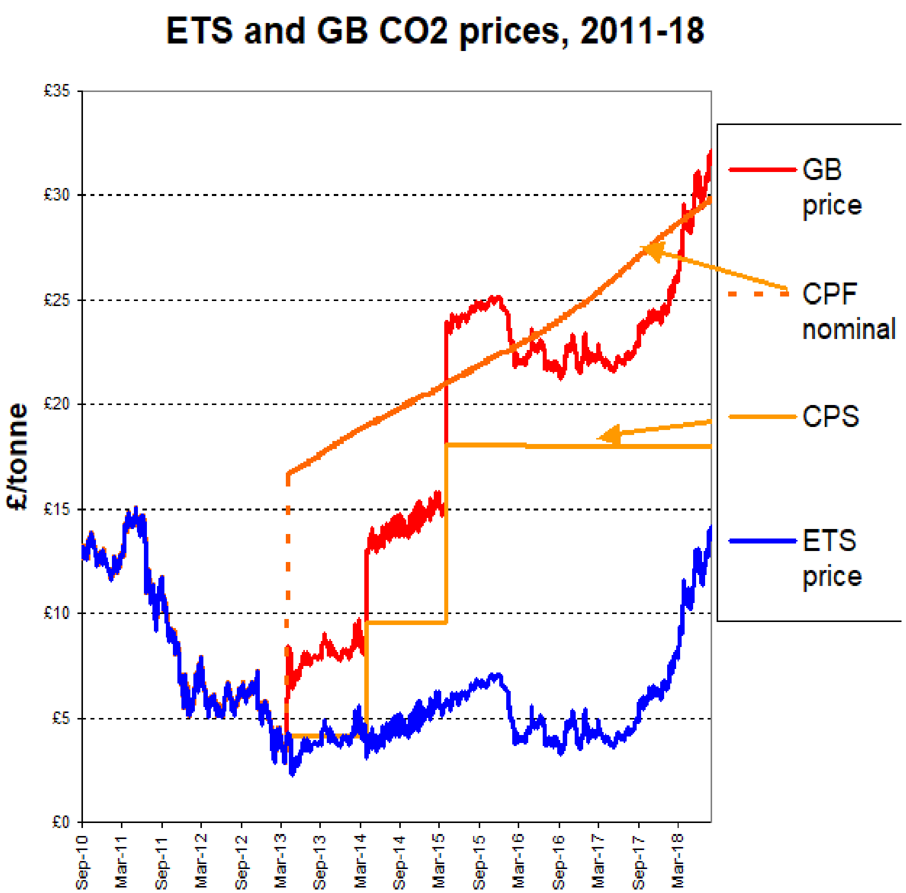
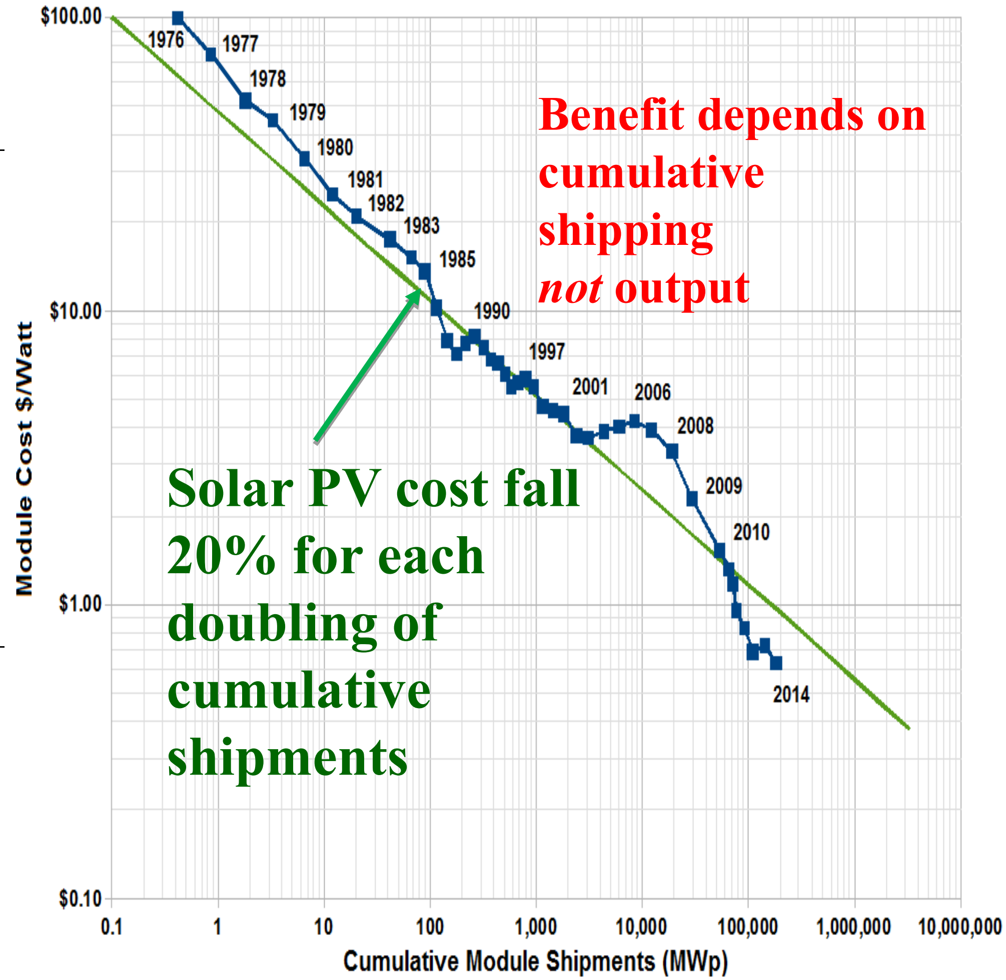
Address external costs (CO_2) and learning benefits





EU Club Goods

- **EU ETS prices CO_2**
  - **Stiglitz Report:** Paris target-consistent price at least **US$40–80/t$CO_2$** by 2020 and US$50–100/tCO_2 by 2030
  - March 2021 EUA price €40/t CO_2 = **$48/t CO_2**
- **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 Accelerating the Clean Energy Revolution ***bal** learning subsidies*

Clean Energy Package

- 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

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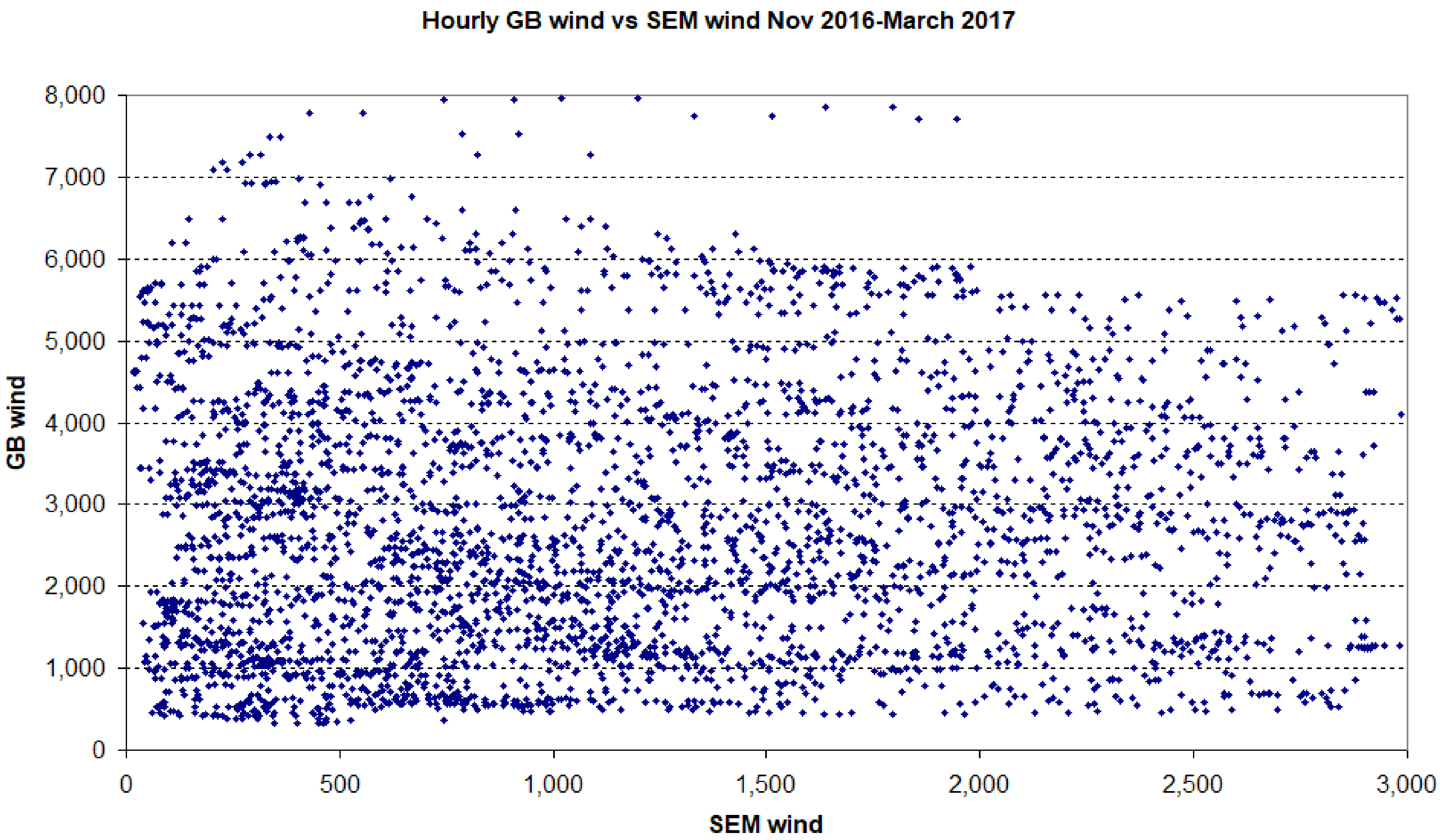
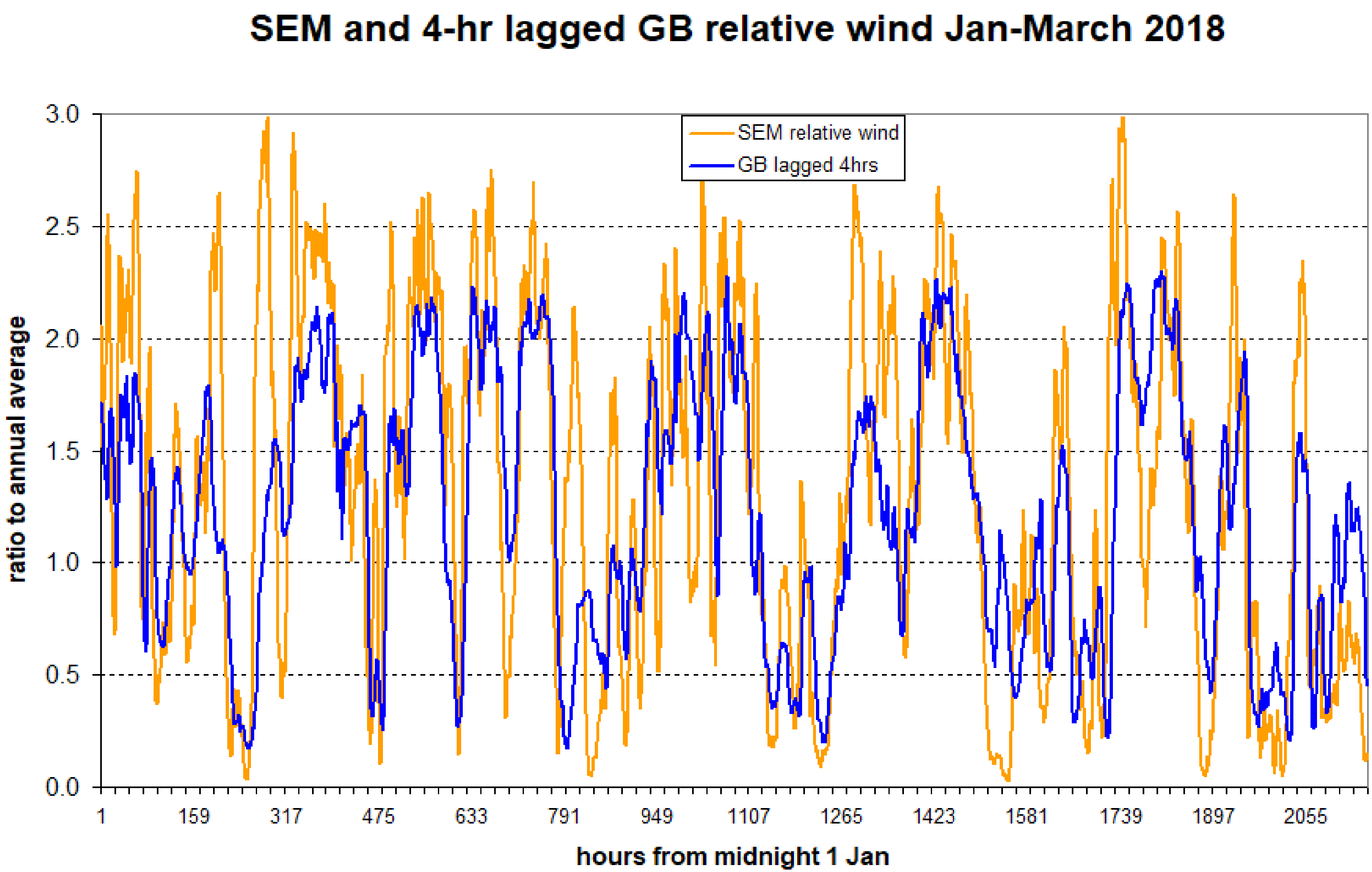
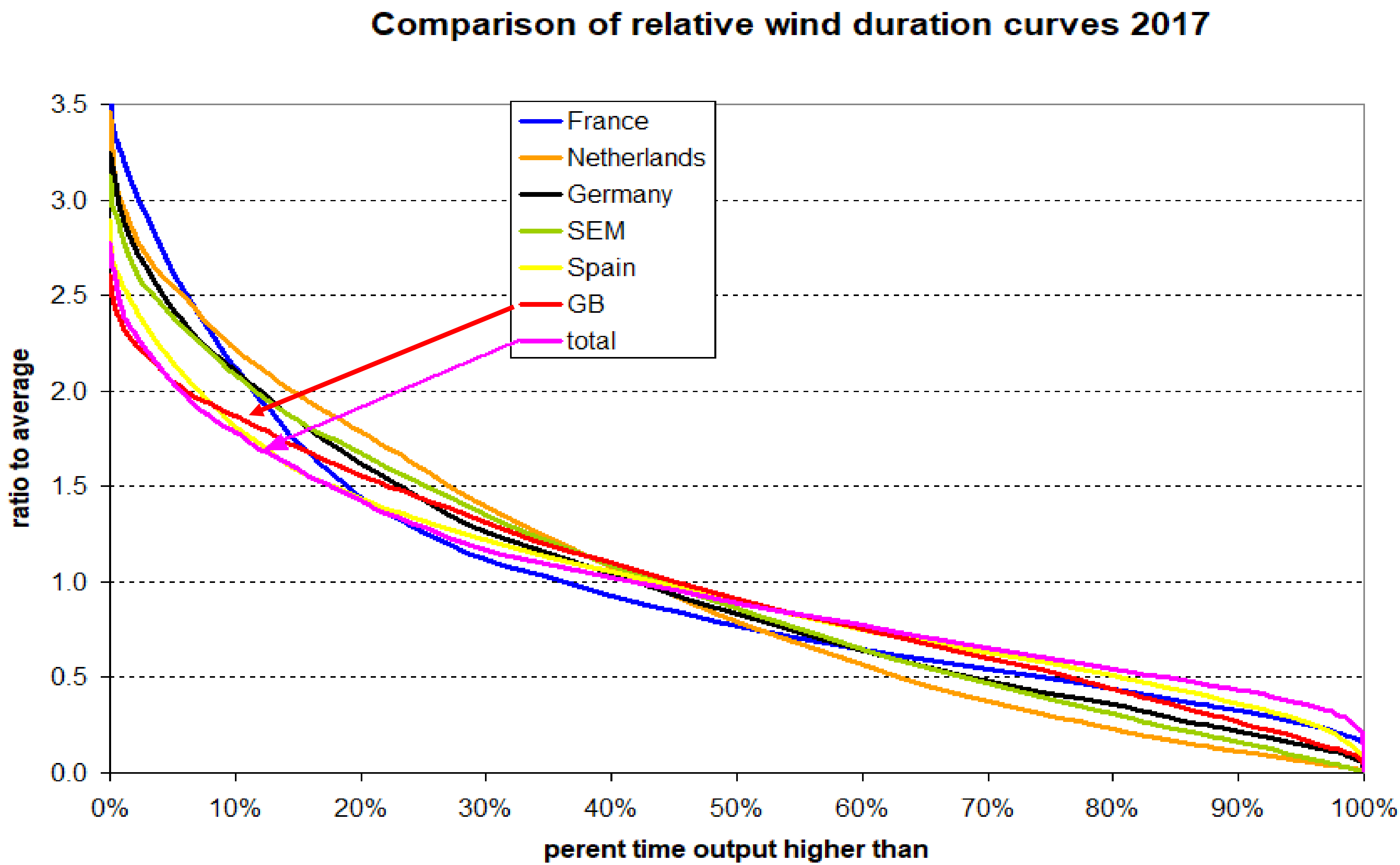
SEM wind *appears* uncorrelated with GB wind – interconnnection good?



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



Ability for SEM to export constrained by surpluses abroad



SEM System constraints

- 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 to1.9 GWh ***if enabled***

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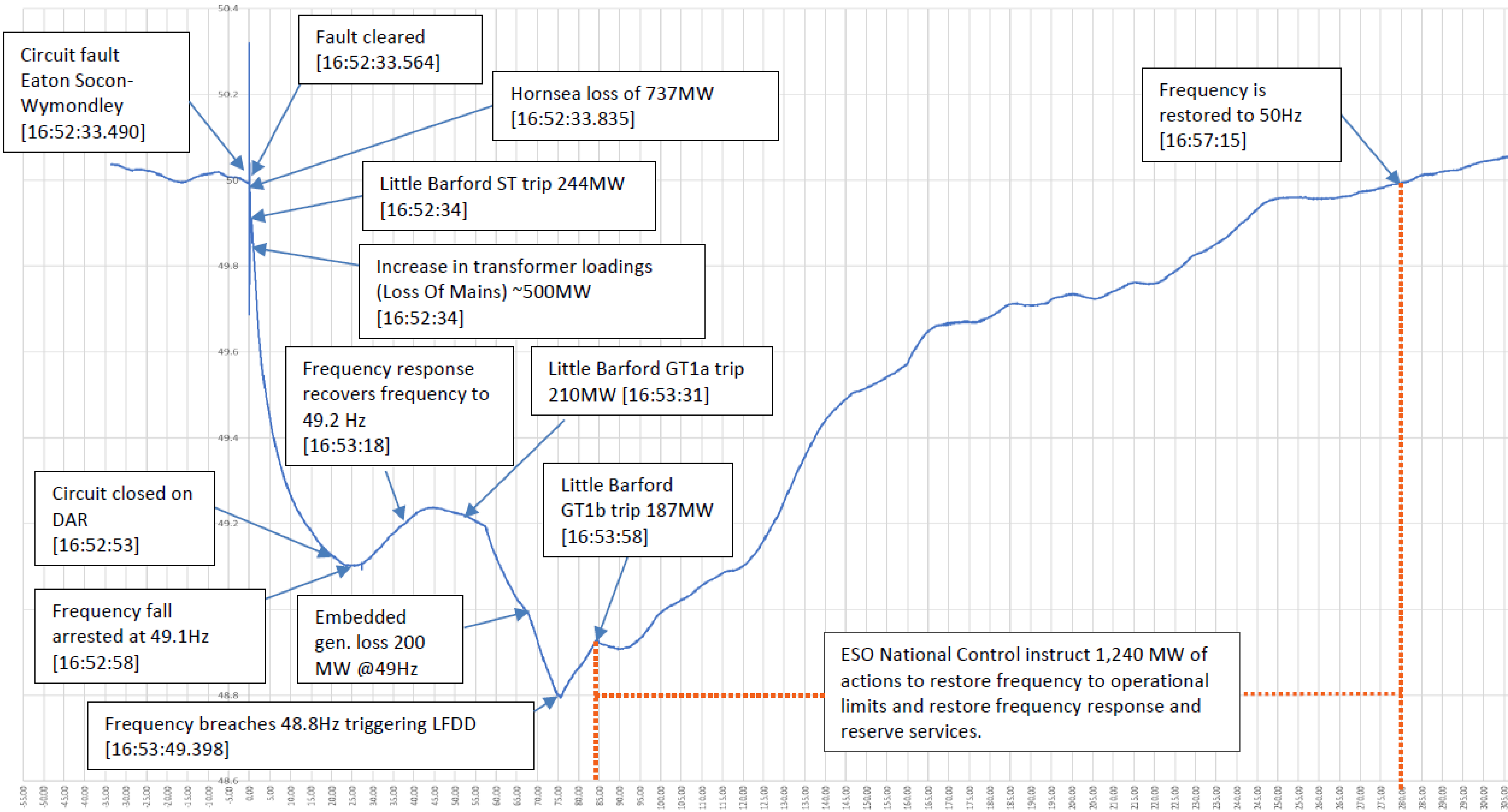
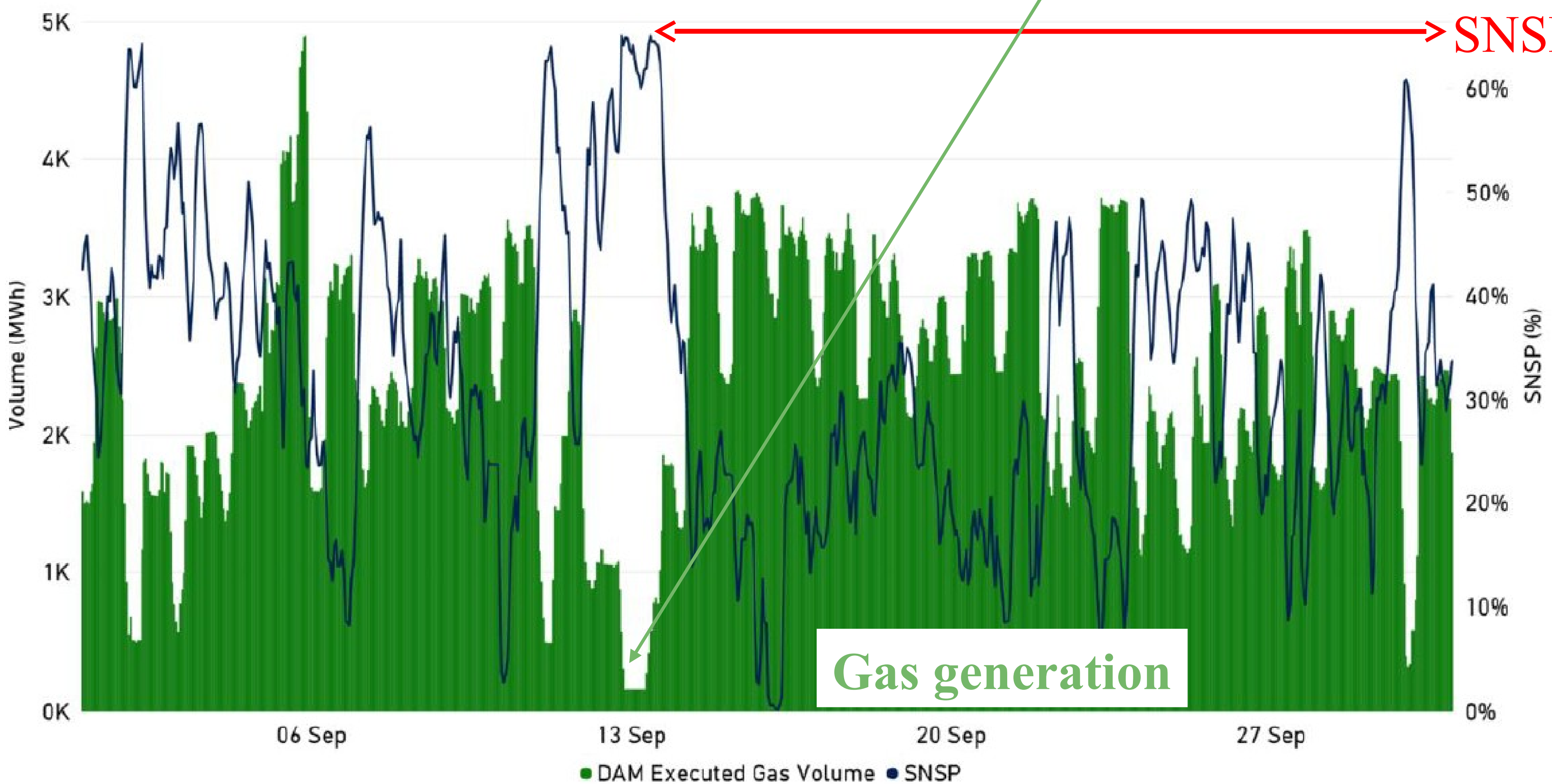
Frequency evolution in GB in Aug 2019 blackout



SNSP needs fossil generation



Graph 11 - DAM Executed Gas Volume against SNSP

Source: Market Monitoring Unit, SEM

Modelling SEM in 2026

- 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**

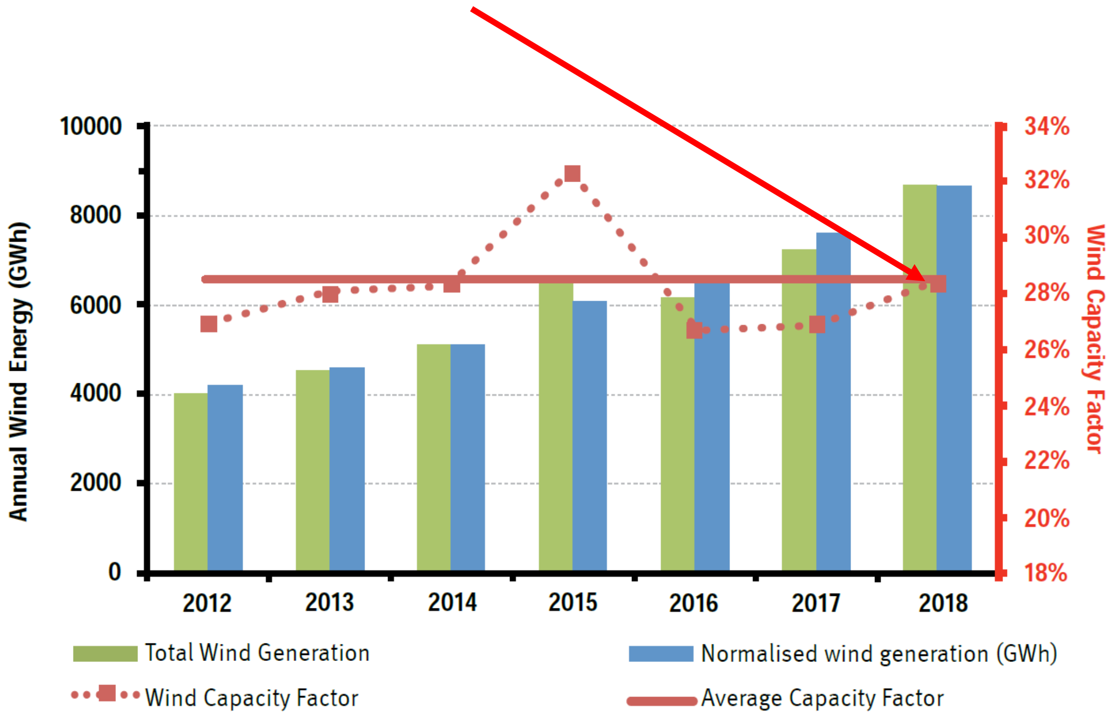


Figure 20 - The actual and normalised annual energy produced from wind power in Ireland over the last six years. In red are the figures for annual wind capacity factor, and their average

Source: Eirgrid (2019)

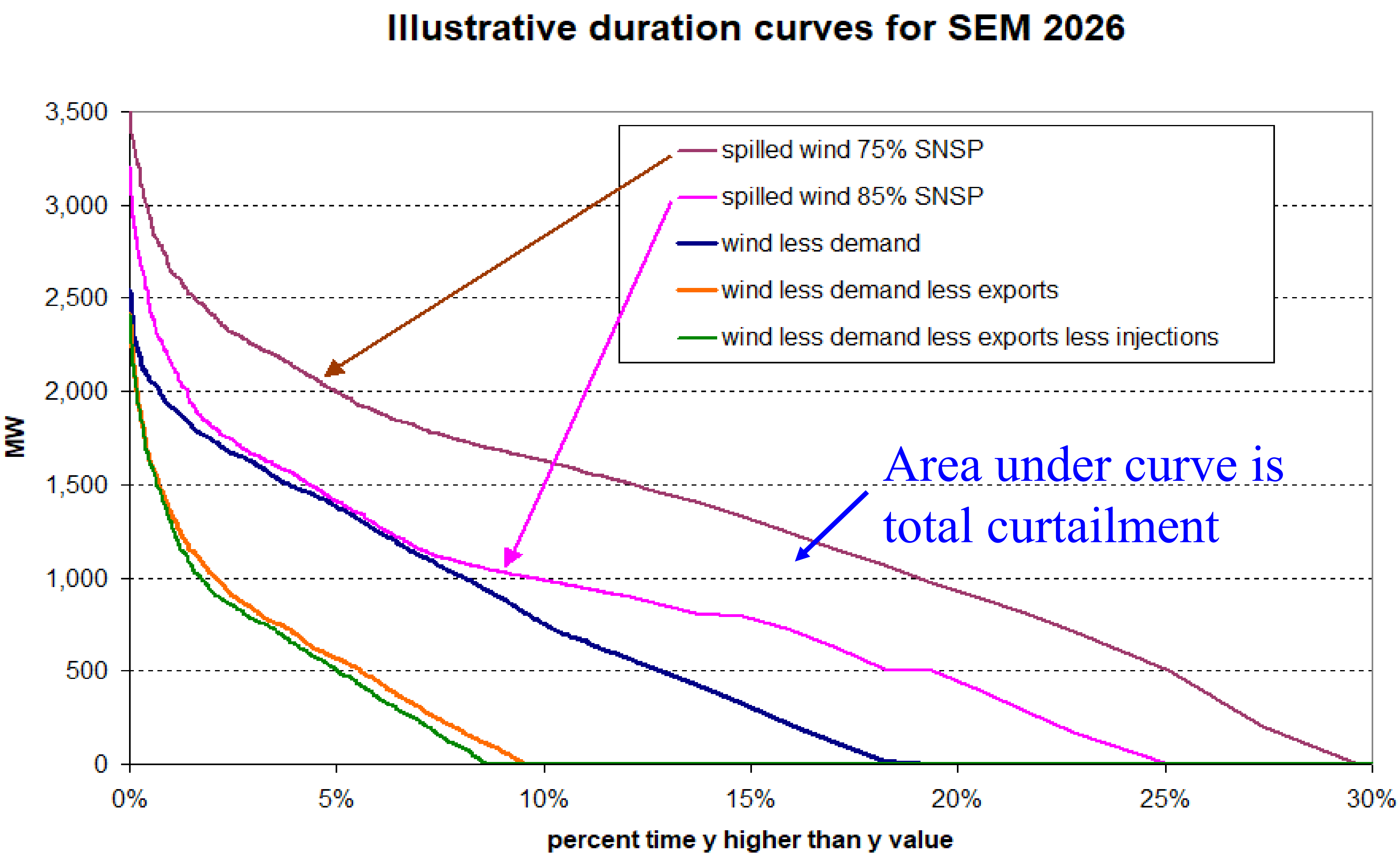
Steps to find curtailment

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

Curtailment and SNSP



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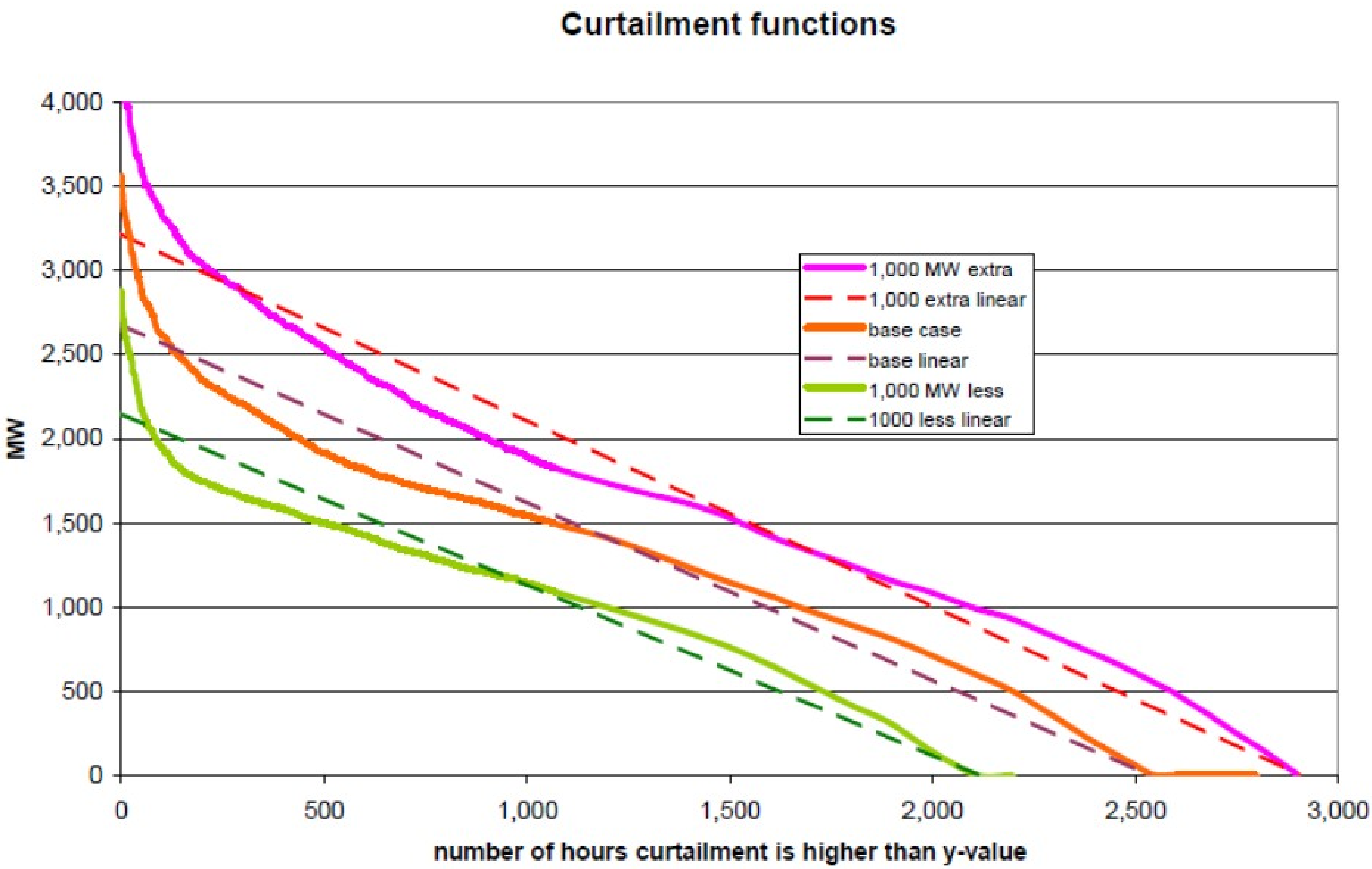
Linearizing allows simple algebraic curtailment model



Impacts of SNSP on curtailment

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

Solve for social optimum

1. Cost of fossil capacity to meet reliability standard, $C_f(W)$
2. Differentiate w.r.t W = 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_ϵ 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** $\tau = M_W - S_W.$

Sources of market failure

- 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

Corrective charge

The corrective charge has two components

$$\tau(W) = r_P(E\lambda\phi_\lambda/L - \delta_W) + (v_p - v_W)E\lambda\phi_\lambda + v_F\beta\phi_{H-h^*}W\frac{\partial h^*}{\partial W} > 0$$

excess capacity credit — marginal curtailment

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,

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

β = (1- SNSP) - fraction met by synchronous plant for frequency stability,

$\varphi_{H\text{-}h^*}$ = 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,

Calibration

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

Curtailment 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

Policy options

- 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)

Conclusions

- 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)

References

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Spare slides

Is battery storage the answer to excess 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

Interconnector impacts

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

Algebraic model of curtailment

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

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

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

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

Calibrate algebraic model

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*