Club Goods and a ‘Tragedy of the Commons’
Renewable energy: learning and curtailment

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EPRG, University of Cambridge
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
Address external costs (CO₂) and learning benefits

- Benefit depends on cumulative shipping not output
- Solar PV cost fall 20% for each doubling of cumulative shipments
• EU ETS prices CO$_2$
  – **Stiglitz Report**: Paris target-consistent price at least **US$40–80/tCO$_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**
  **Global** 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
SEM wind *appears* uncorrelated with GB wind – interconnection 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 to 1.9 GWh if enabled

Newbery
Frequency evolution in GB in Aug 2019 blackout

- Circuit fault Eaton Socon-Wymondley [16:52:33.490]
- Fault cleared [16:52:33.564]
- Hornsea loss of 737MW [16:52:33.835]
- Little Barford ST trip 244MW [16:52:34]
- Increase in transformer loadings (Loss Of Mains) ~500MW [16:52:34]
- Frequency response recovers frequency to 49.2 Hz [16:53:18]
- Little Barford GT1a trip 210MW [16:53:31]
- Frequency falls arrested at 49.1Hz [16:52:58]
- Embedded gen. loss 200 MW @49Hz
- Little Barford GT1b trip 187MW [16:53:58]
- Frequency breaches 48.8Hz triggering LFDD [16:53:49.398]
- ESO National Control instruct 1,240 MW of actions to restore frequency to operational limits and restore frequency response and reserve services.
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

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

Illustrative duration curves for SEM 2026

Area under curve is total curtailment
Linearizing allows simple algebraic curtailment model
### Impacts of SNSP on curtailment

Increasing SNSP has large impact

<table>
<thead>
<tr>
<th>SNSP</th>
<th>Curtail GWh</th>
<th>percent</th>
<th>Delta GWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>75%</td>
<td>3,388</td>
<td>13.3%</td>
<td></td>
</tr>
<tr>
<td>80%</td>
<td>2,642</td>
<td>10.4%</td>
<td>746</td>
</tr>
<tr>
<td>85%</td>
<td>2,050</td>
<td>8.1%</td>
<td>592</td>
</tr>
<tr>
<td>90%</td>
<td>1,826</td>
<td>7.2%</td>
<td>224</td>
</tr>
</tbody>
</table>
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

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

where the () is the annual fixed cost, $r_W$, of 1 MW wind, $v_W$ is the unit variable cost, $\phi_e$ is the effective capacity factor over the uncurtailed hours, $H-h^*$.
4. Find the market surplus (revenue less cost) $M_W$
5. 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
The corrective charge has two components:

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

- **excess capacity credit**
- **marginal curtailment**

Choose \( \delta_W \) to make zero

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

\( E\lambda \phi_\lambda \) = Expected wind output in these hours, \( \delta_W \) = derating factor,

\( (v_p - v_W) E\lambda \phi_\lambda \) = Operating costs then (tiny)

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

\( \phi_{H-h^*} \) = wind capacity factor at the curtailment margin,

\( v_p \) = 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 $\delta_w$ 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


Spare slides
Is battery storage the answer to excess wind?

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

<table>
<thead>
<tr>
<th>Extra MW BES</th>
<th>Curtail GWh/yr</th>
<th>Delta GWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2,042</td>
<td>8.0%</td>
</tr>
<tr>
<td>100</td>
<td>2,023</td>
<td>8.0%</td>
</tr>
<tr>
<td>200</td>
<td>2,006</td>
<td>7.9%</td>
</tr>
</tbody>
</table>

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

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

Less than 3% of potential storage capacity
## Interconnector impacts

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

<table>
<thead>
<tr>
<th>SNSP</th>
<th>curtailed GWh/yr</th>
<th>percent</th>
<th>saved by Celtic Link, GWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>75%</td>
<td>3,153.7</td>
<td>12.4%</td>
<td>235</td>
</tr>
<tr>
<td>80%</td>
<td>2,392.3</td>
<td>9.4%</td>
<td>250</td>
</tr>
<tr>
<td>85%</td>
<td>1,775.1</td>
<td>7.0%</td>
<td>275</td>
</tr>
<tr>
<td>90%</td>
<td>1,515.4</td>
<td>6.0%</td>
<td>310</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>SNSP</th>
<th>curtailed GWh/yr</th>
<th>percent</th>
<th>saved by current IC GWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>75%</td>
<td>4,085.0</td>
<td>16.1%</td>
<td>697</td>
</tr>
<tr>
<td>80%</td>
<td>3,393.3</td>
<td>13.3%</td>
<td>751</td>
</tr>
<tr>
<td>85%</td>
<td>2,907.2</td>
<td>11.4%</td>
<td>858</td>
</tr>
<tr>
<td>90%</td>
<td>2,752.8</td>
<td>10.8%</td>
<td>927</td>
</tr>
</tbody>
</table>
Let $F$ be fossil capacity, $W$ wind capacity, $D(h)$ is demand duration schedule, $L$ is Loss of Load Expectation, $\delta$ de-rating factor, then

$$F \delta_F = D(L) - W \delta_W,$$

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 $\phi$ and $H$ hrs/yr

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

Newbery
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)
Duration curves: each ranked separately