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MIT Center for Energy and Environmental Policy Research

# Energy storage: recent developments and future potential

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*and Imperial College London*

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http://www.eprg.group.cam.ac.uk

# Outline

- Why storage?
- What substitutes?
- How much is there?
- How much do you need?
- What does it cost?
- What is it worth?
- Conclusions

Research supported by Imperial College London under FP7 project *e-Storage*

# Why storage?

- Increased intermittency – shift supply and/or demand to when/where needed

=> Ancillary services: inertia, fast frequency response, back-up reserves

- Not new: Dinorwig Pumped Storage built to shift nuclear
- Recent developments:
  - Increased wind/solar
  - Reduced battery costs
  - Rise in battery electric vehicles
  - Smart meters and demand side aggregators

**What are the sources of demand/supply shifting?**
**What are their costs?**

# Dinorwig PSP
# 1.8 GW 9.1 GWh

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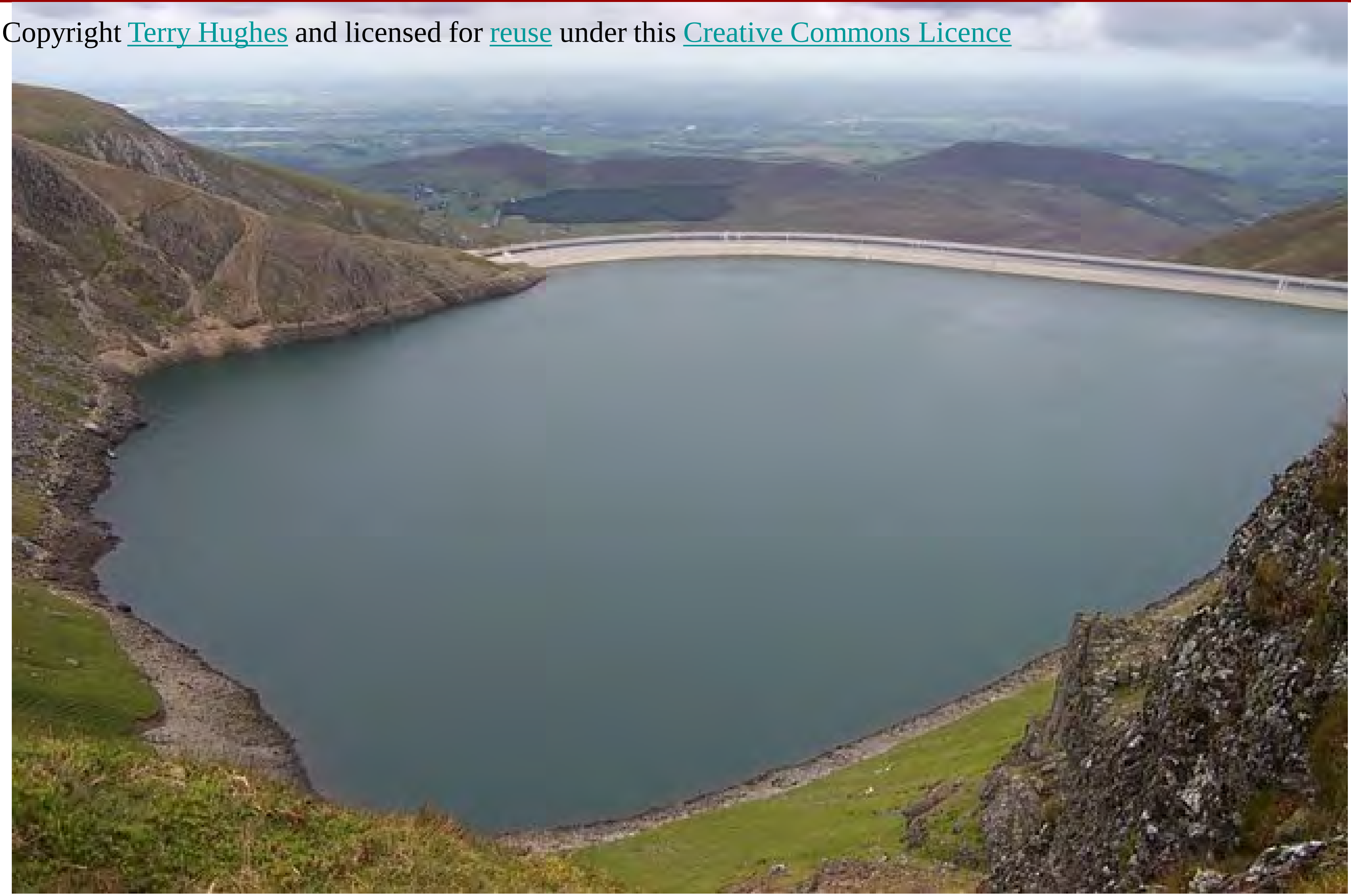

# Physics

- Gravitational storage **weak** compared to chemical storage
- 1 AA battery = 100 kg raised 10 m

=> need a lot of weight raised a lot (lots of water high up)

=> or a very heavy train running up and down a mountain

- **PSPs**: distant, 100+ yr life, flexible (30 secs)
  - Typical cycle time daily, storage 6-9 hrs,
- **Storage dams**: distant, 100+ yr life, high output and storage
  - Seasonal (months), energy rather than capacity limited, flexible
- **Batteries**, close by, short life, very flexible (< 1 sec)
  - Typical cycle time 15 mins – hrs

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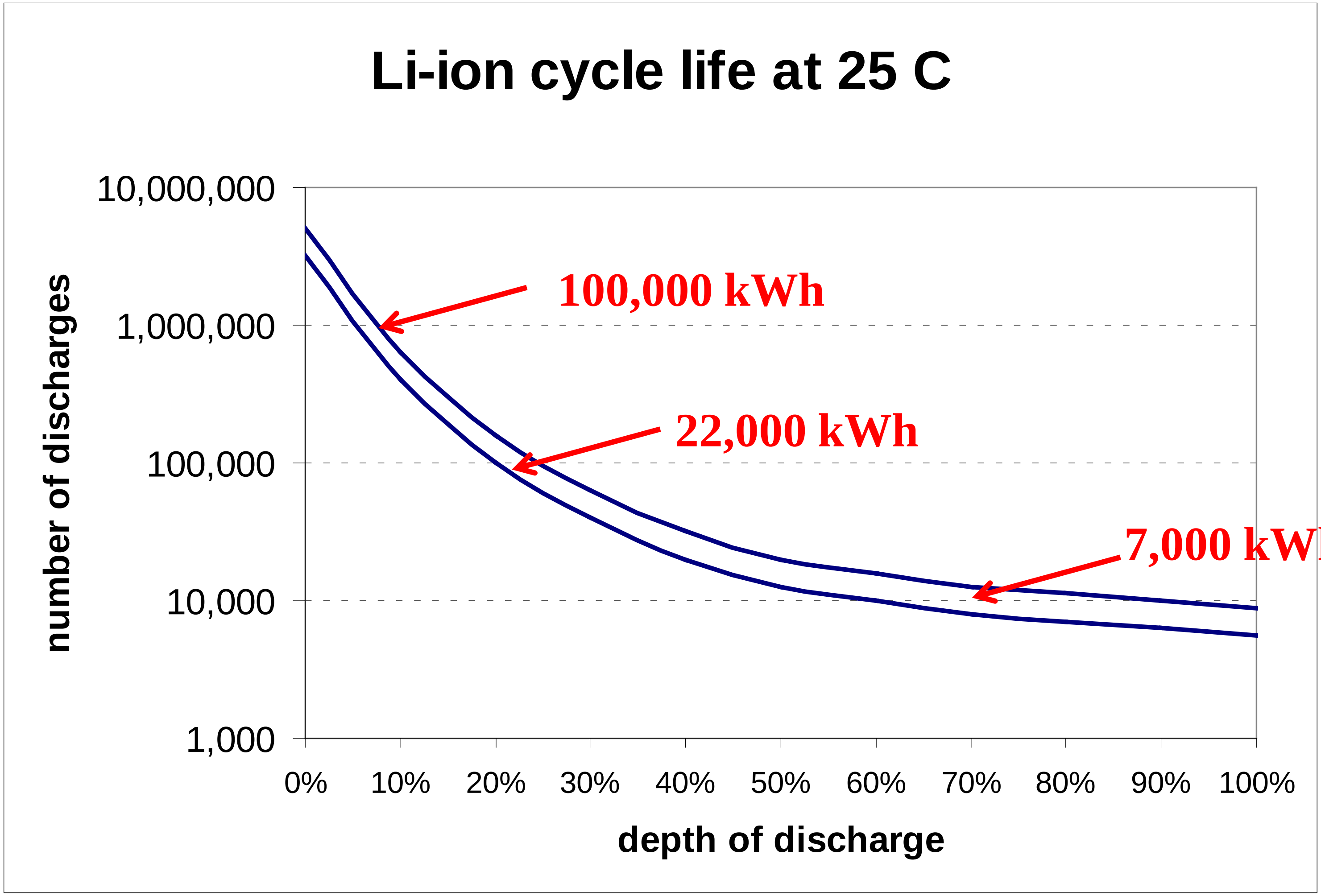
# Advanced Rail Energy Storage (ARES)

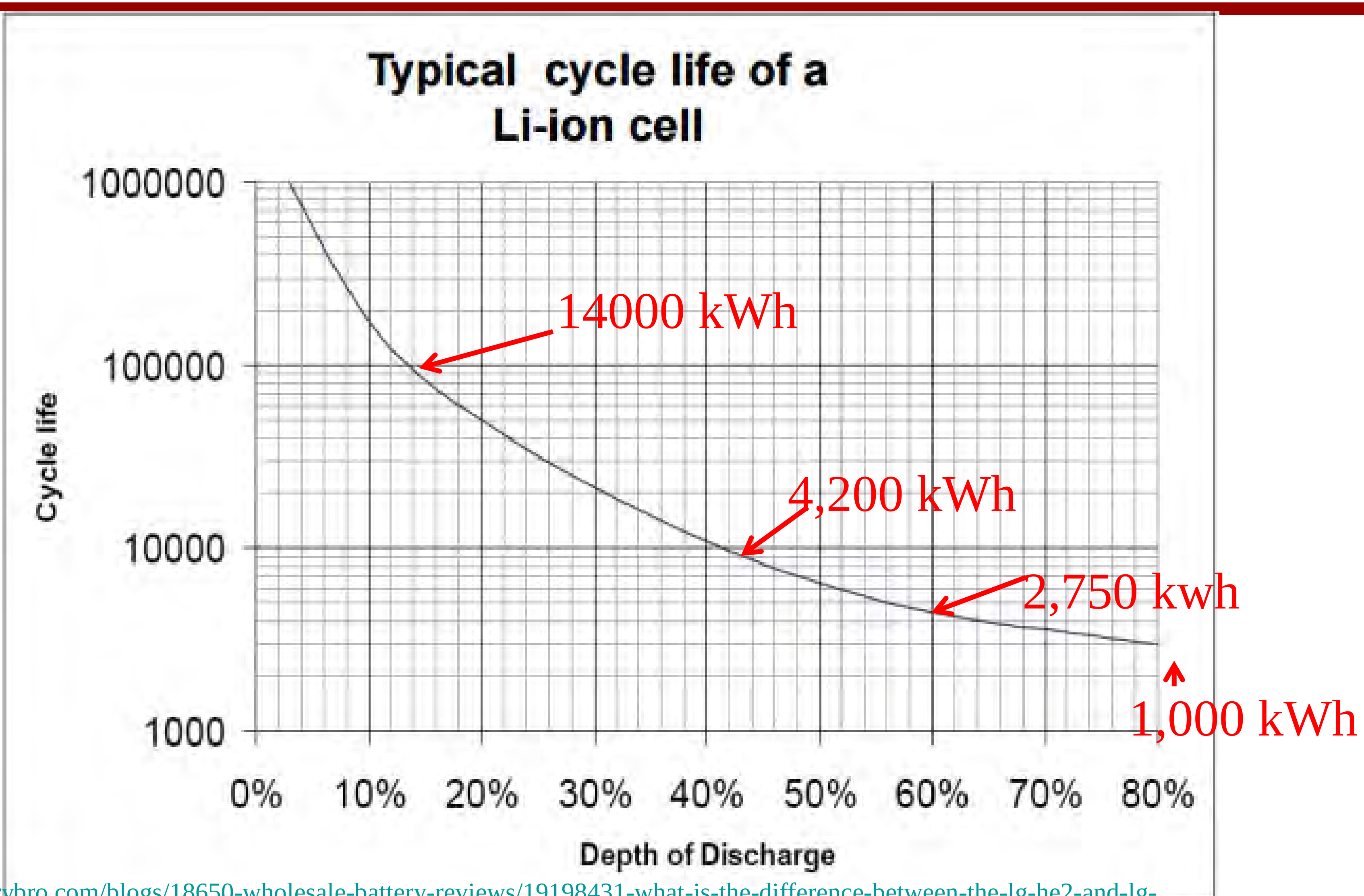
http://www.forbes.com/sites/jamesconca/2016/05/26/batteries-or-train-pumped-energy-for-grid-scale-power-storage/#1742f1237de5

# Lifetime per kWh capacity




From www.saftbatteries.com/.../li_ion_battery_life__TechnicalSheet_en_0514_Protected.pdf

# Not all sources agree




https://batterybro.com/blogs/18650-wholesale-battery-reviews/19198431-what-is-the-difference-between-the-lg-he2-and-lg-he4-which-is-newer-better

# Options

- Can **shift** supply and/or demand over time and space

Time
  - Pumped storage plant (PSP)
  - Batteries
  - Change pattern of hydro-electric output (indirect storage)
  - Change time pattern of charging BEVs (indirect storage)
  - Shift demand (for heat, cold, refrigeration, wet appliances, pumping etc.)
- Space
  - Interconnectors, stronger transmission
- Can curtail RES, replace by reserve capacity

***How much, what cost?***

# How much?

- World **pumped storage** capacity 2016 = **164 GW**
  - Growing for past 8 years at 2.7% p.a.
  - **Estimated at 99.7% of global bulk electric storage**
  - **Storage capacity** at 12 hrs = **2.9 TWh**
  - GB 2.9 GW PSP, **27 GWh** storage = **9.3 hrs**
  - Germany 6.8 GW PSP, **50 GWh** storage = **7.4 hrs**
- World **hydro** 2012 = **979 GW, 3,288 TWh/yr =16% total**
  - Growing for past 8 years at 3.4% p.a.
  - **Storage capacity** at 3 months = **2,144 TWh**
  - **Norway 23.4 GW storage hydro, 70 TWh = 125 days**
- Global electro-chemical **batteries**:
  - **1.6 GW, 3 GWh, 0.1% of EES**

# What about Electric cars?

- 2035 world car fleet 1.2 bn; 10% BEVs, 20kWh = 2.4 TWh
  - C.f. dams have 2,000+ TWh
- UK: if 5 million BEVs by 2035 (13% fleet)
  - 20kWh each => 100 GWh; 30 km/day = 6 kWh/day
  - 50% charging at 3 kW at 5.30 p.m. = **8 GW extra load at peak**
  - 8% charging at any moment = **1.2 GW shiftable load**
- Really good idea to control time of charging
- Helpful (but modest) ability to demand shift
- Fast frequency response also useful

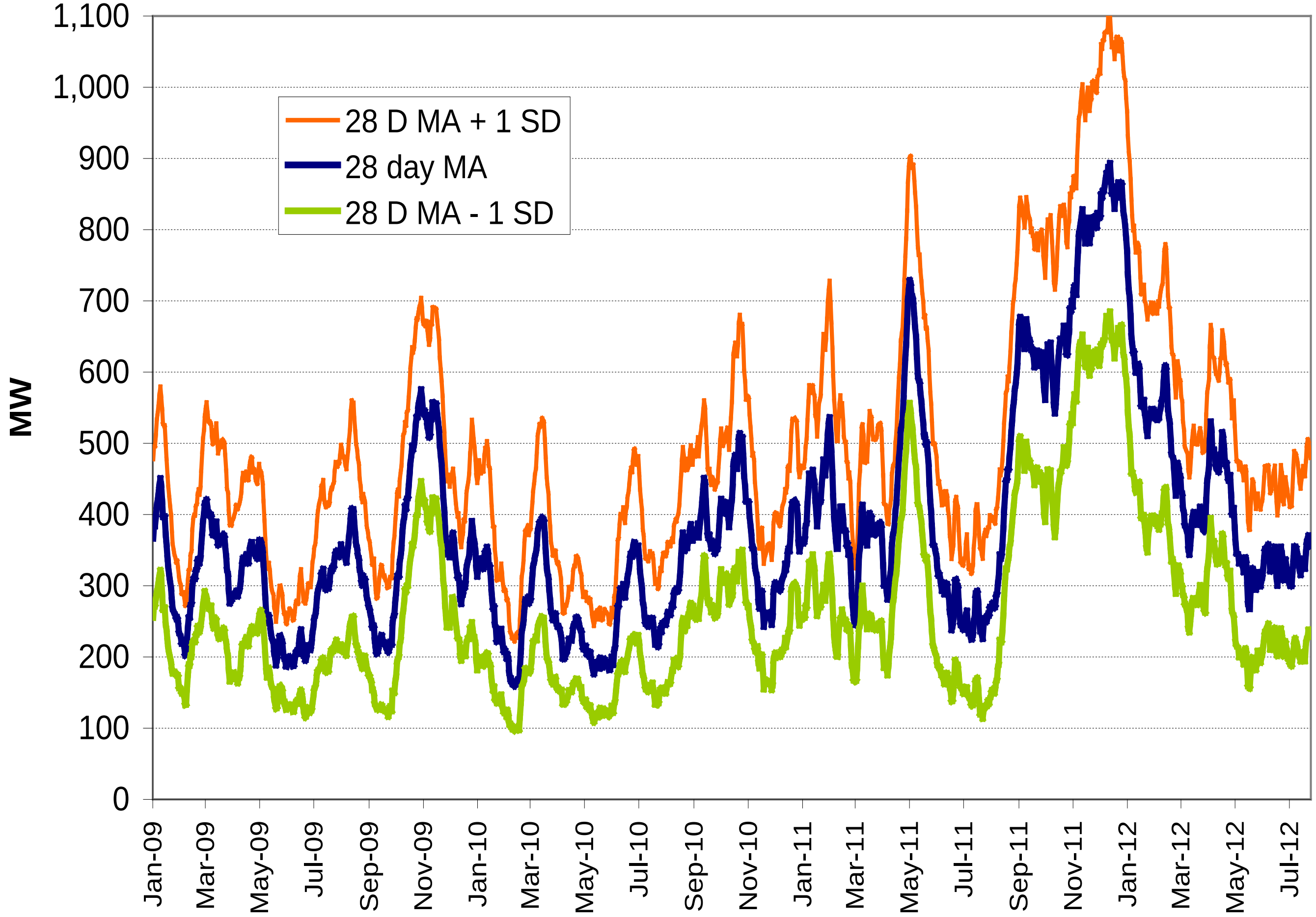
***BEVs can harm a lot or help somewhat***

# How much do you need?

- Entirely reliant on renewables?
  - PV capacity factor 10-15%? Peak = 6-10 times average
    - **None at night!**
  - Wind on-shore 20-30%? Off-shore 30-45%?? Peak 3-5 x average
    - Correlates better with demand in UK
- Germany Energiewende future RES excess capacity could be 60 GW in some hours, store 24 hrs = 1,440 GWh
  - Current PSP = 50 GWh so **expand by 29 times**
  - Longer term storage proportional
- US what-if: 2 TW for 1 day = 48 TWh = 400 PSPs with 250 m head, 8,500 sq km lakes, 600 MW + lots of concrete

# Island of Ireland –the cutting edge of penetration

## Monthly mean wind output and variability in the SEM



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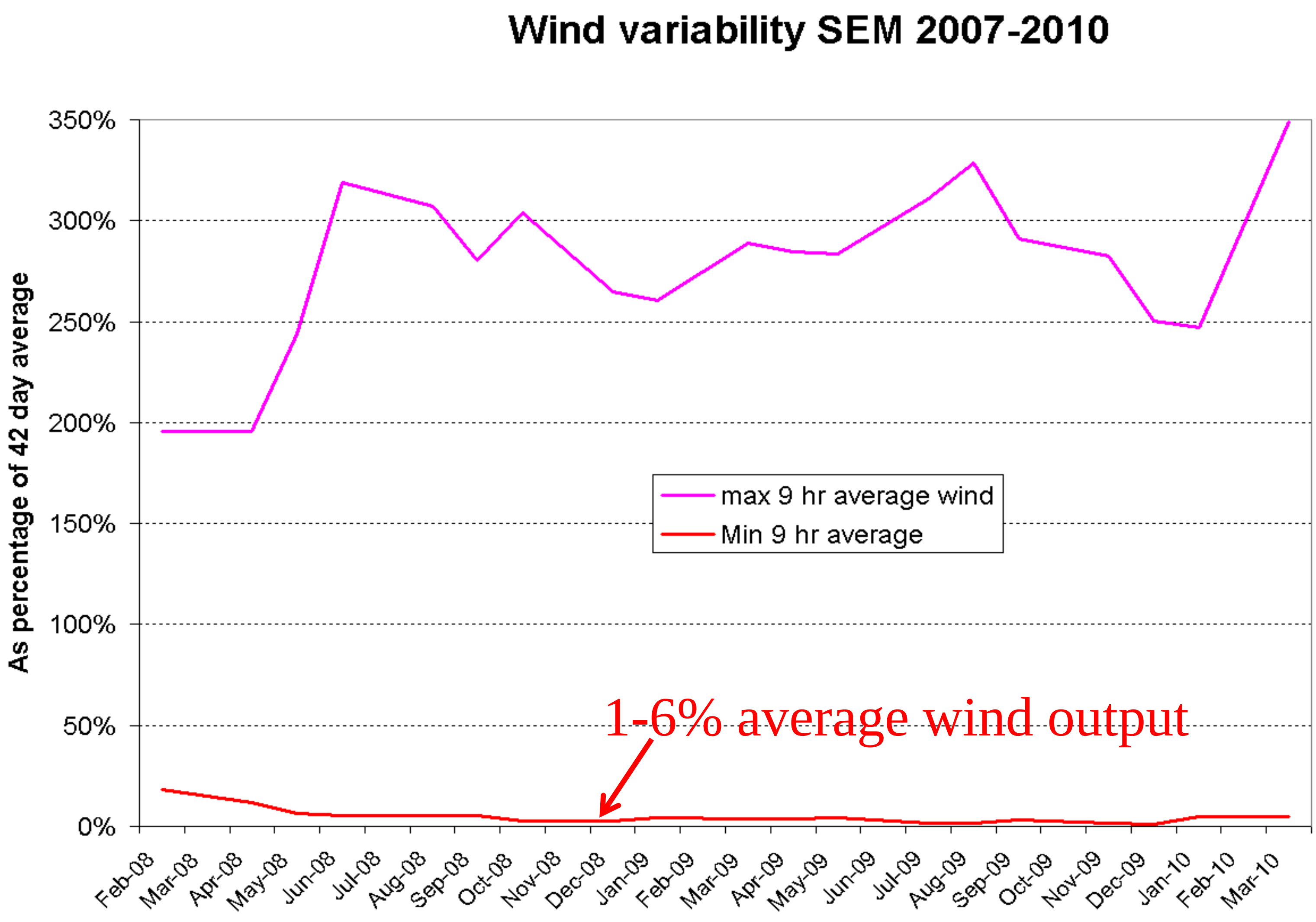
# Averaging over 9 hrs in successive 42 day periods



# Cost of PSPs

**Capital costs**

- Dinorwig perhaps £(2012) 162/kWh (?)
- Turlough Hill (Ireland) £50/kWh (?)
- DECC calculator £500-£5000/kW, default = £2,100
  - If for 8 hours = £63-625/kWh, default = **£260/kWh**

**Operating cost**

- £10-15/MWh (?), but 25% losses

=> losses less important buying when power cheap

# Battery costs

**Capital cost**

- Nissan Xstorage £3,200 for 4.2kWh = £762/kWh
- Tesla Powerwall $3,000 for 7kWh = **$430/kWh (2015)**
- Element Energy (2012) optimistic projected cost **2020** for electric vehicle pack $(2012) 5,950 for 24 kWh = **$250/kWh**
- 2015 estimates (2012)400/kWh in 2014; **$300/kWh in 2018**.

**Operating cost**

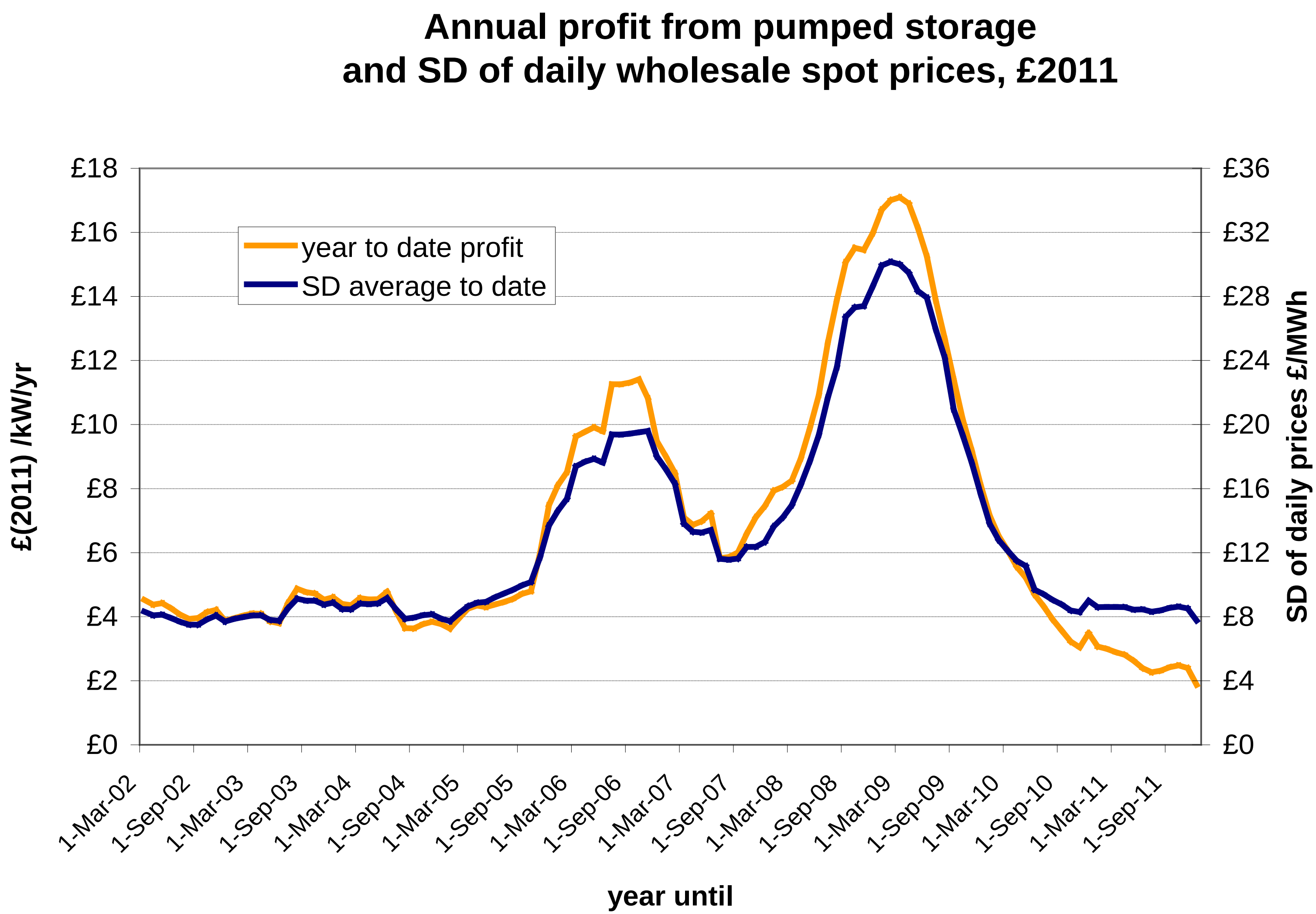
- 20-25% losses
- Main cost is depreciation: 60% DoD: 3000 kWh/kWh capacity $10/MWh cycle cost?
  - Much cheaper for high frequency modest discharge

# EES overhead costs

| | cost/kWh capacity | DoD | O&M /kW.yr | cycles/ day | Life yrs. | levelized cost/MWh |
|---|---|---|---|---|---|---|
| Leighton Buzzard Li-ion NOAK | £850 | 100% | £10 | 1 | 9 | £251 |
| Leighton Buzzard Li-ion NOAK | £850 | 75% | £13 | 2 | 10 | £264 |
| Tesla 2018 Low | $475 | 100% | $15 | 1 | 12 | $207 |
| Tesla 2018 High | $1,050 | 60% | $20 | 2 | 14 | $323 |
| Li-Ion 2020 Low | $385 | 100% | $15 | 1 | 12 | $175 |
| Li-Ion 2020 High | $525 | 100% | $20 | 2 | 6 | $179 |
| Na-S Low | $420 | 100% | $15 | 1 | 7 | $256 |
| Na-S high | $700 | 80% | $20 | 2 | 6 | $287 |
| Lead-acid low | $196 | 100% | $15 | 1 | 1 | $617 |
| Lead-acid high | $280 | 100% | $15 | 1 | 3 | $334 |

| PSP | interest | cost/kWh capacity | DoD | O&M /kW.yr | cycles/day | Life yrs. | levelized cost/MWh |
|---|---|---|---|---|---|---|---|
| Dinorwig | 5% | £162 | 60% | £20 | 1 | 75 | £58 |
| Turlough Hill IE | 5% | £50 | 60% | £20 | 1 | 75 | £32 |
| Cruachan | 5% | £100 | 60% | £20 | 1 | 75 | £43 |
| LEAPS CA | 8% | $183 | 60% | $40 | 1 | 75 | $107 |
| DECC 2050 default | 5% | £260 | 60% | £20 | 1 | 75 | £81 |

# What is PSP worth: arbitrage



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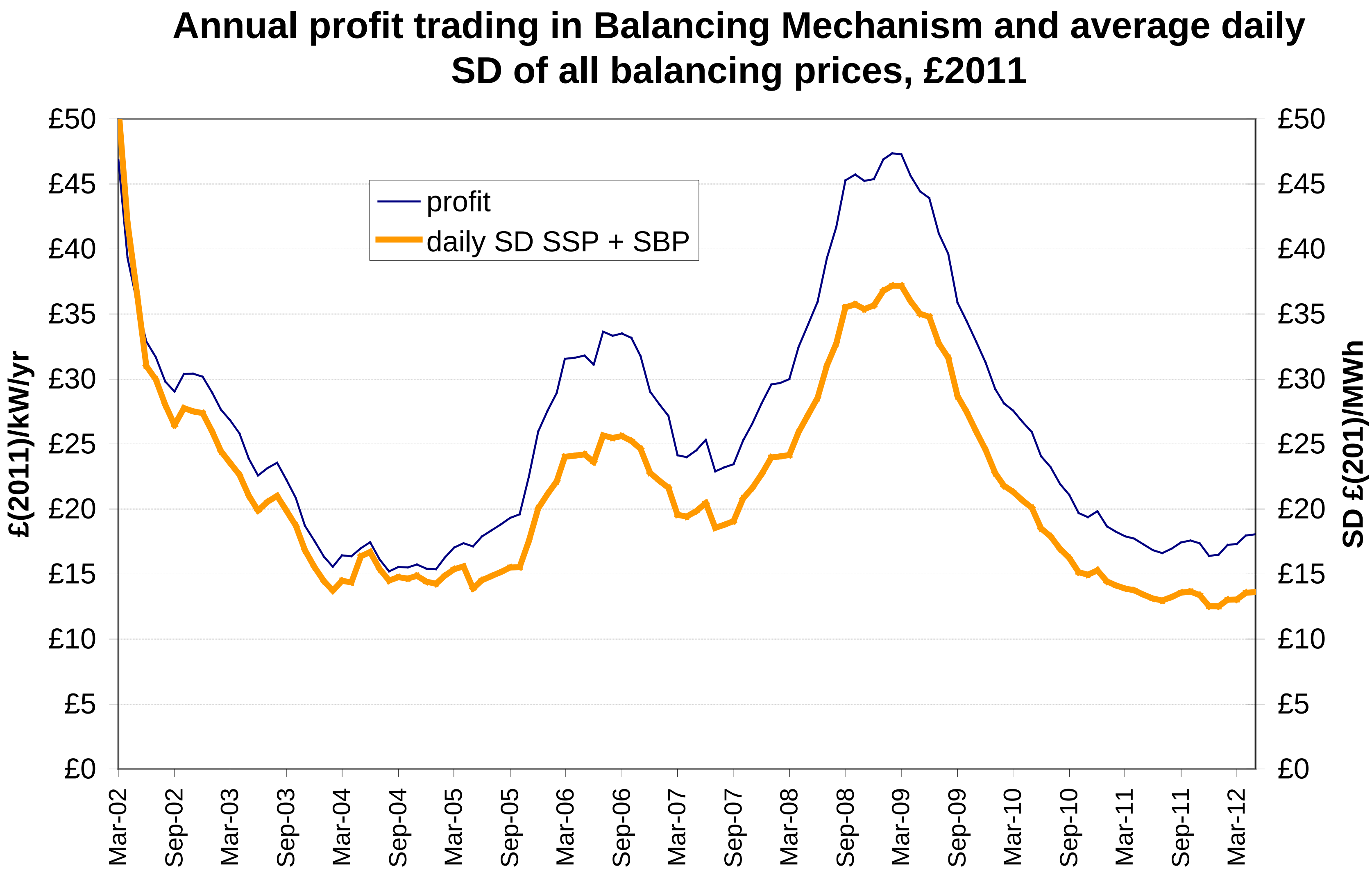
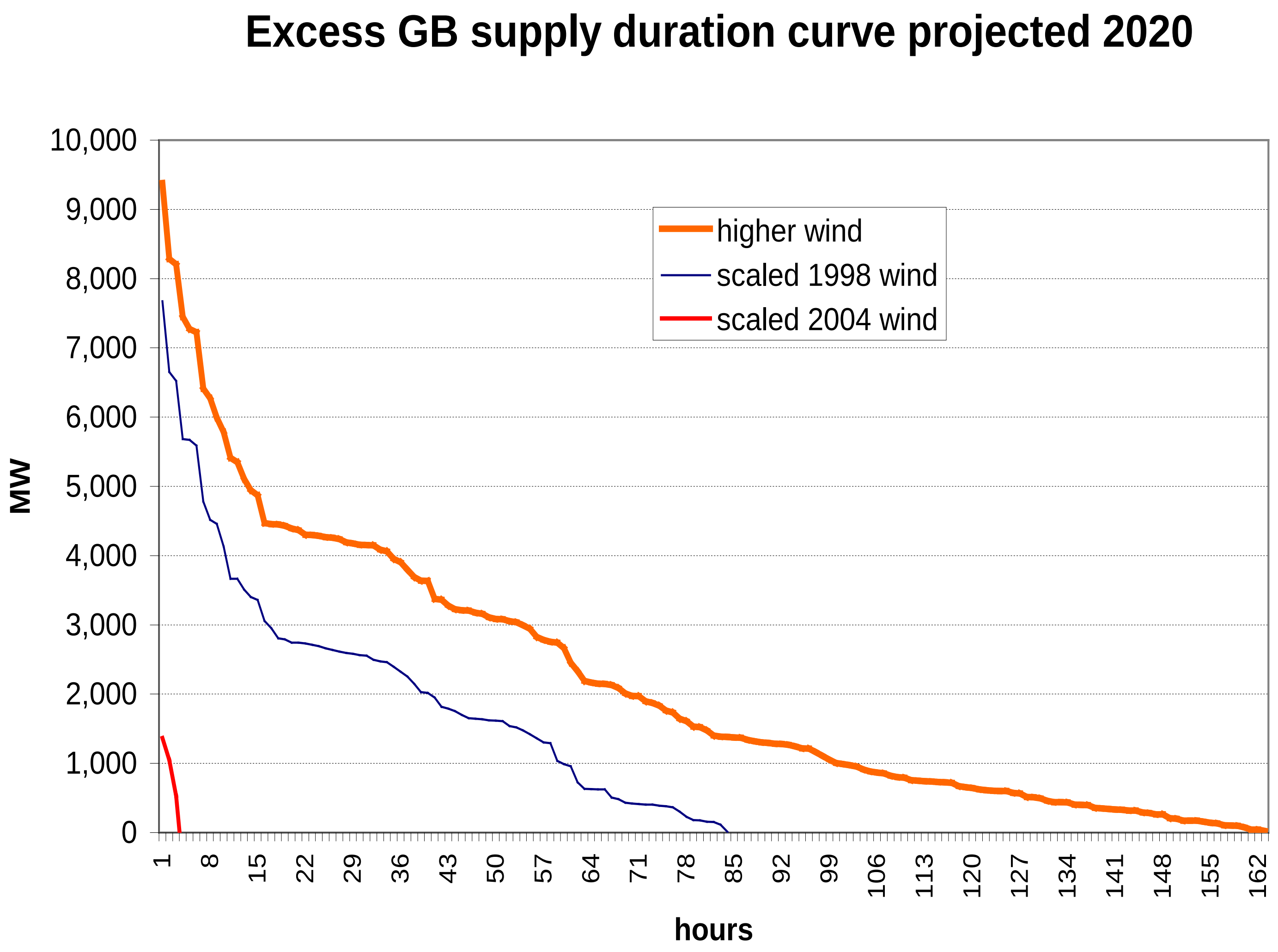
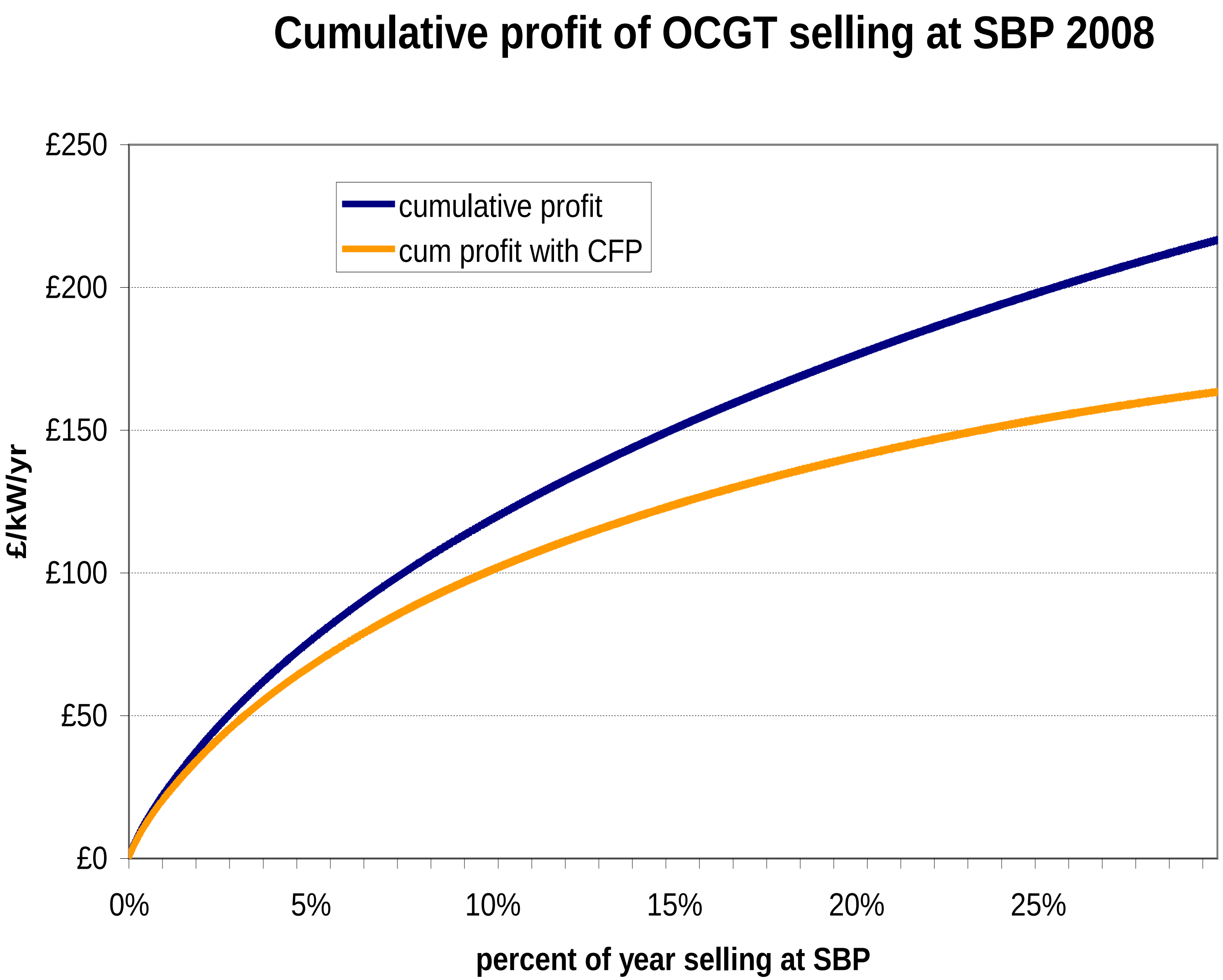
# Balancing more valuable



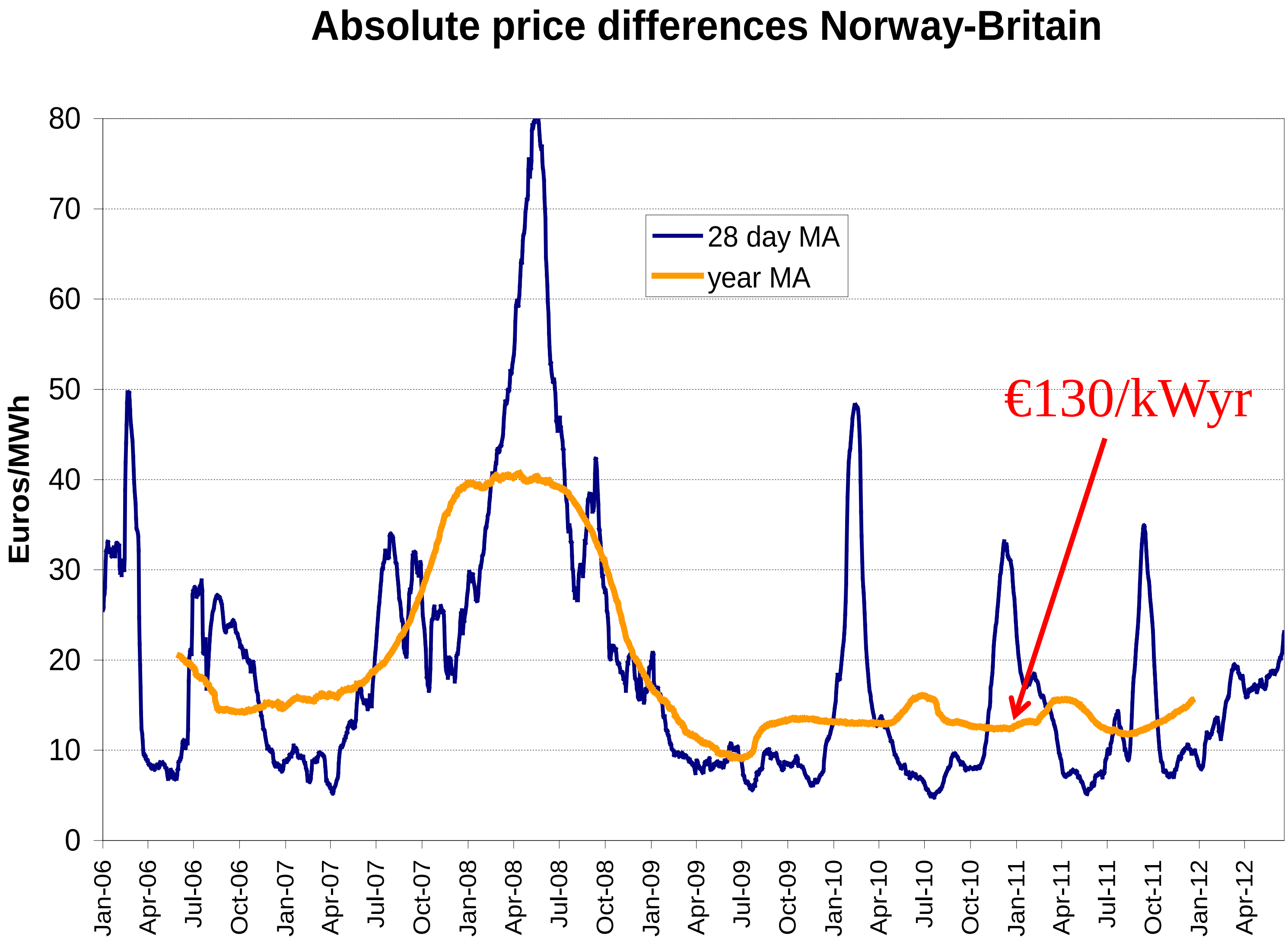
# Wind spilled if no export nor storage



# Back-up generation cheaper?



# Interconnect to Norway



# Conclusions

- Storage has value but is expensive
  - Can arbitrage prices but flexibility services likely more valuable
- PSP useful, storage hydro far larger

=> interconnect to Norway

- Batteries useful for ancillary services
  - And relieving distribution bottlenecks
- Supply and demand shifting over time and space cheaper

=> Back-up generation and interconnection usually cheaper than more storage

***The battery revolution has been over-hyped for the ESI***

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# Acronyms

| | |
|---|---|
| BEV | Battery electric vehicle |
| DoD | Depth of discharge |
| PSP | pumped storage plant |
| RES | renewable electricity supply |
| SEM | Single electricity market of island of Ireland |
| SD | standard deviation |