

Energy storage: recent developments and future potential

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

- 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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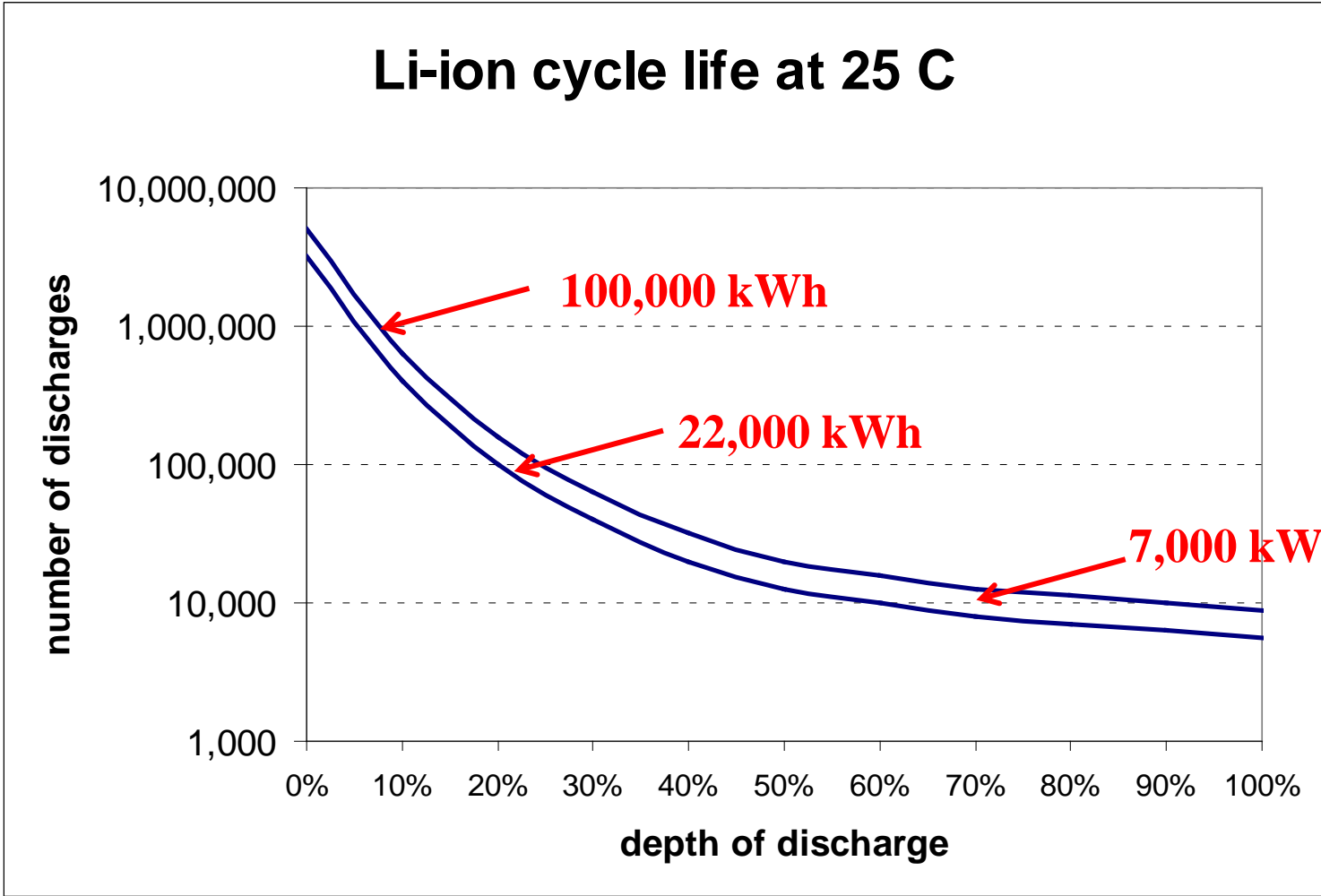
- Gravitational storage **weak** compared to chemical storage
- 1 AA battery = 100 kg raised 10 m
- => need a lot of weight raised a lot (lots of **water** high up)
- => or a very heavy train running up and down a mountain
- **PSPs**: distant, 100+ yr life, flexible (30 secs)
 - Typical cycle time daily, 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

Advanced Rail Energy Storage (ARES)

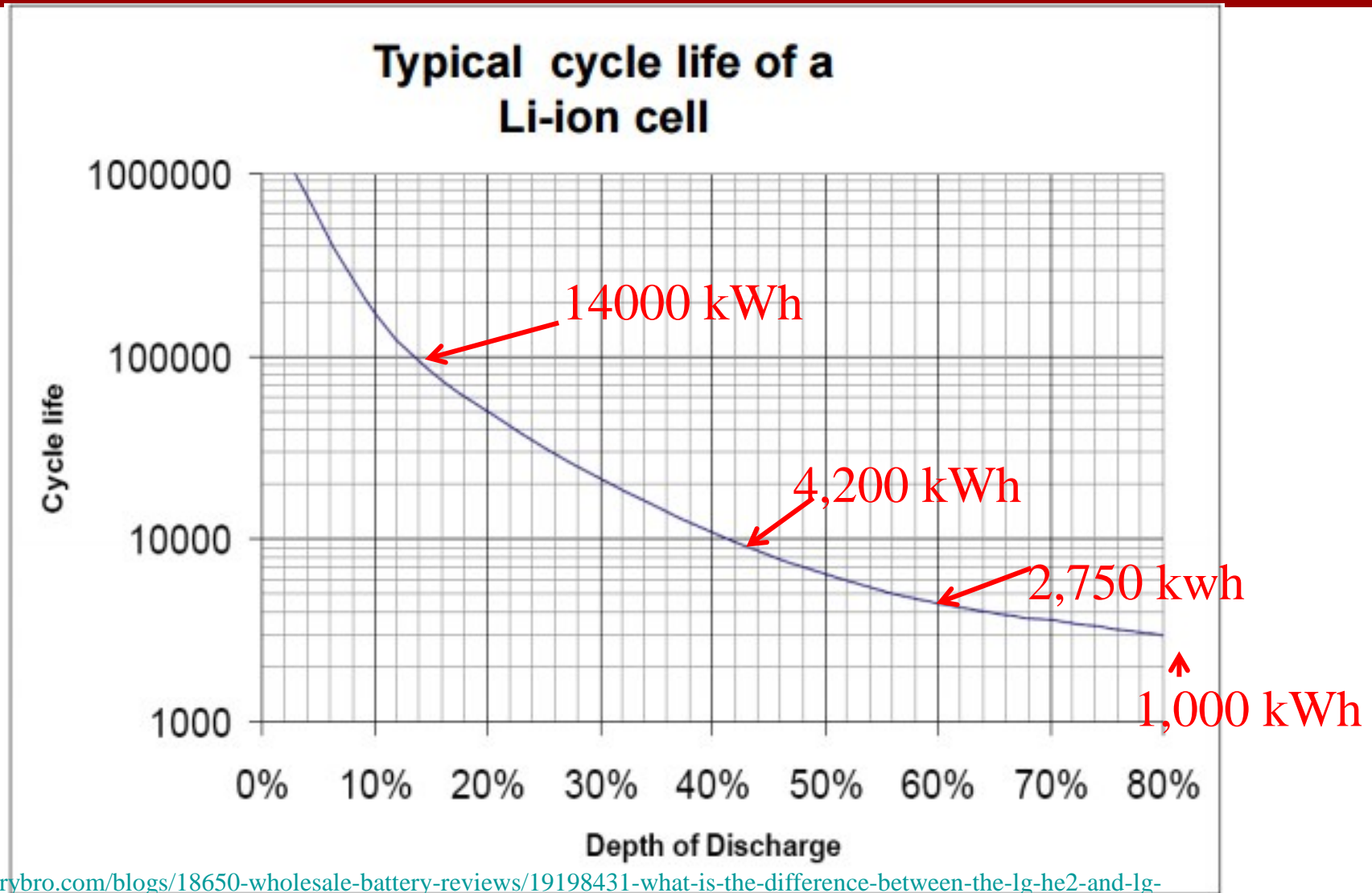


<http://www.forbes.com/sites/jamesconca/2016/05/26/batteries-or-train-pumped-energy-for-grid-scale-power-storage/#1742f1237de5>

Lifetime per kWh capacity



From www.saftbatteries.com/.../li_ion_battery_life_TechnicalSheet_en_0514_Protected.pdf



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

- 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?

- 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**

- 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



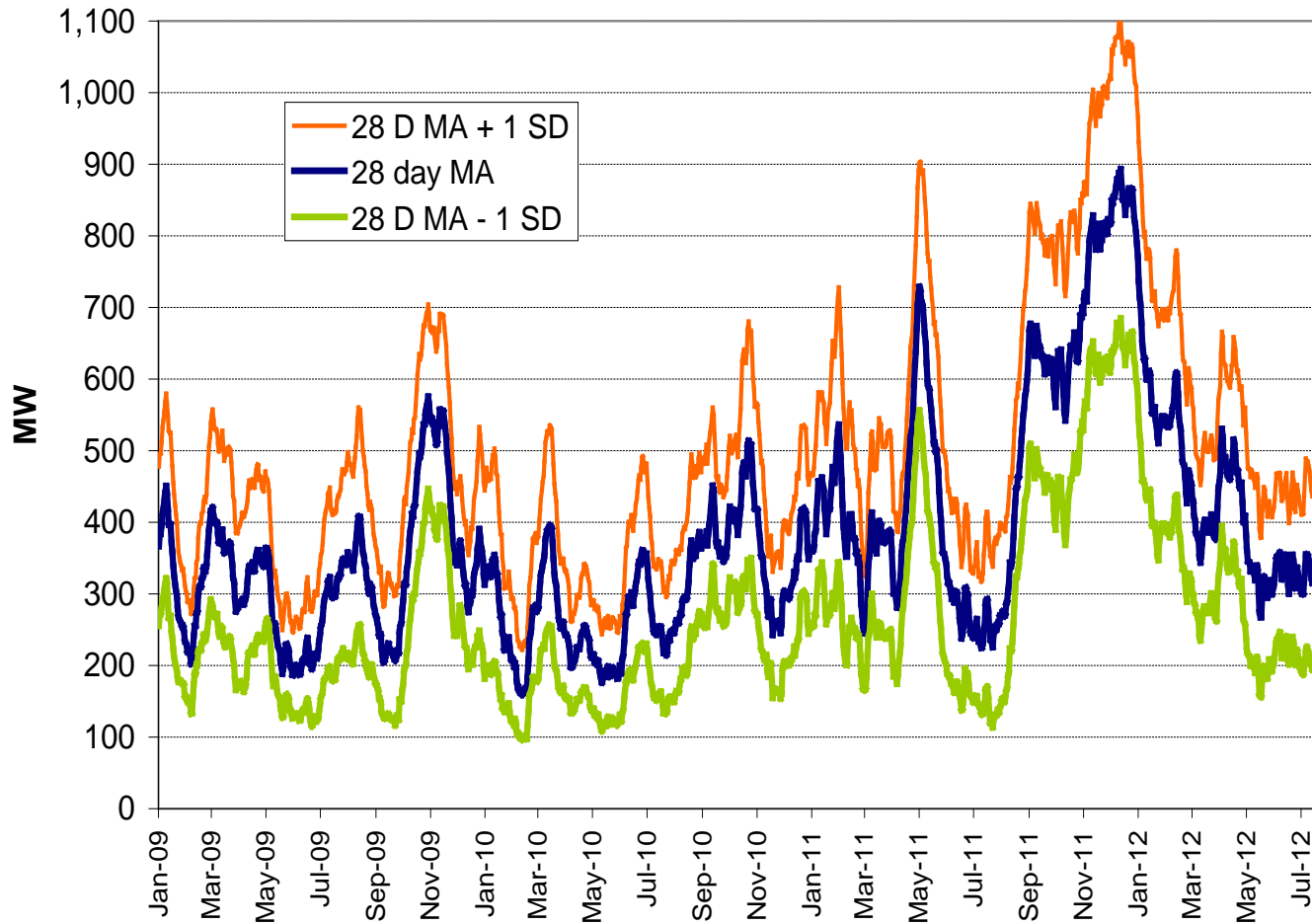
How much do you need?

- 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



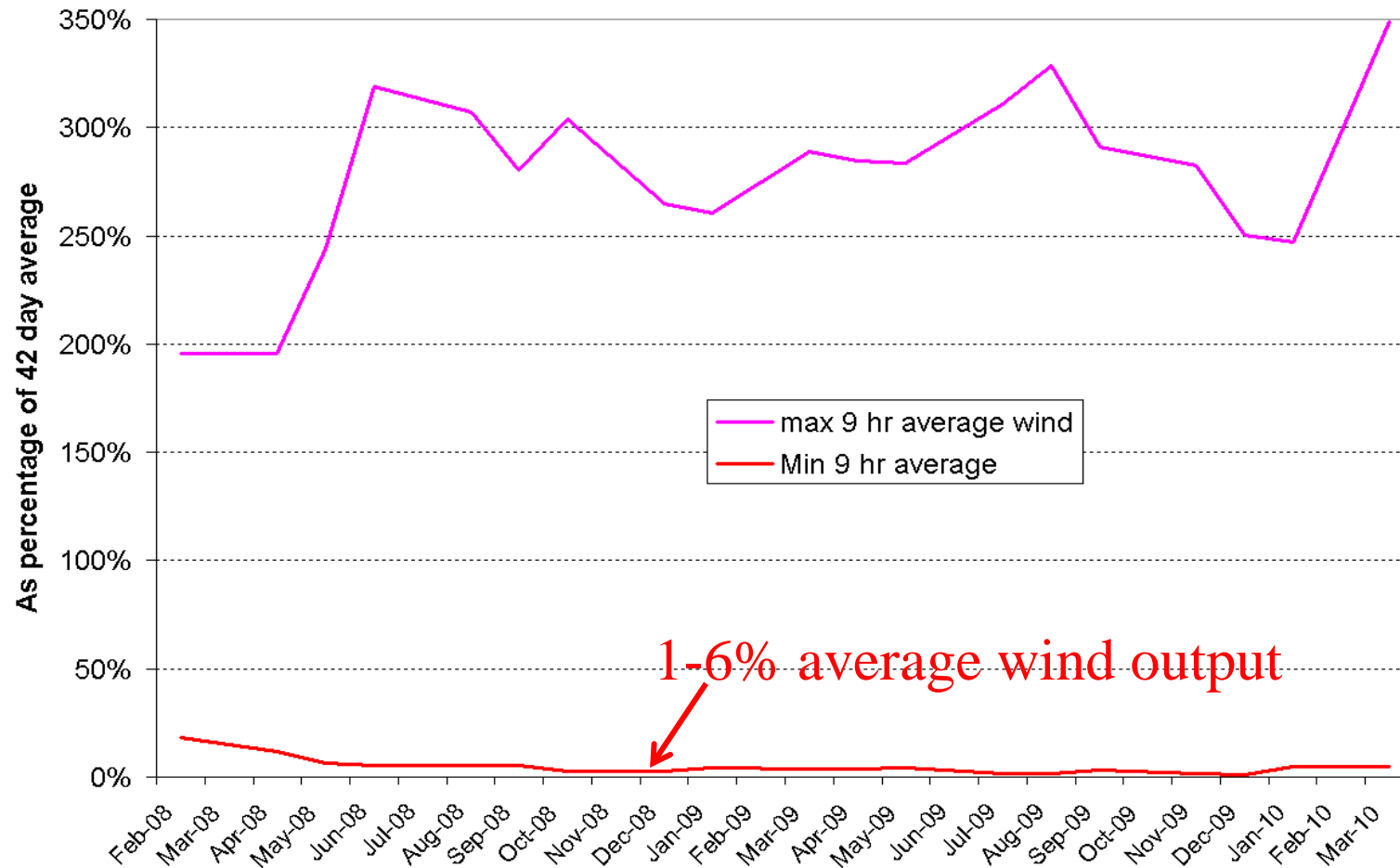
Island of Ireland –the cutting edge of penetration

Monthly mean wind output and variability in the SEM



Averaging over 9 hrs in successive 42 day periods

Wind variability SEM 2007-2010



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

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

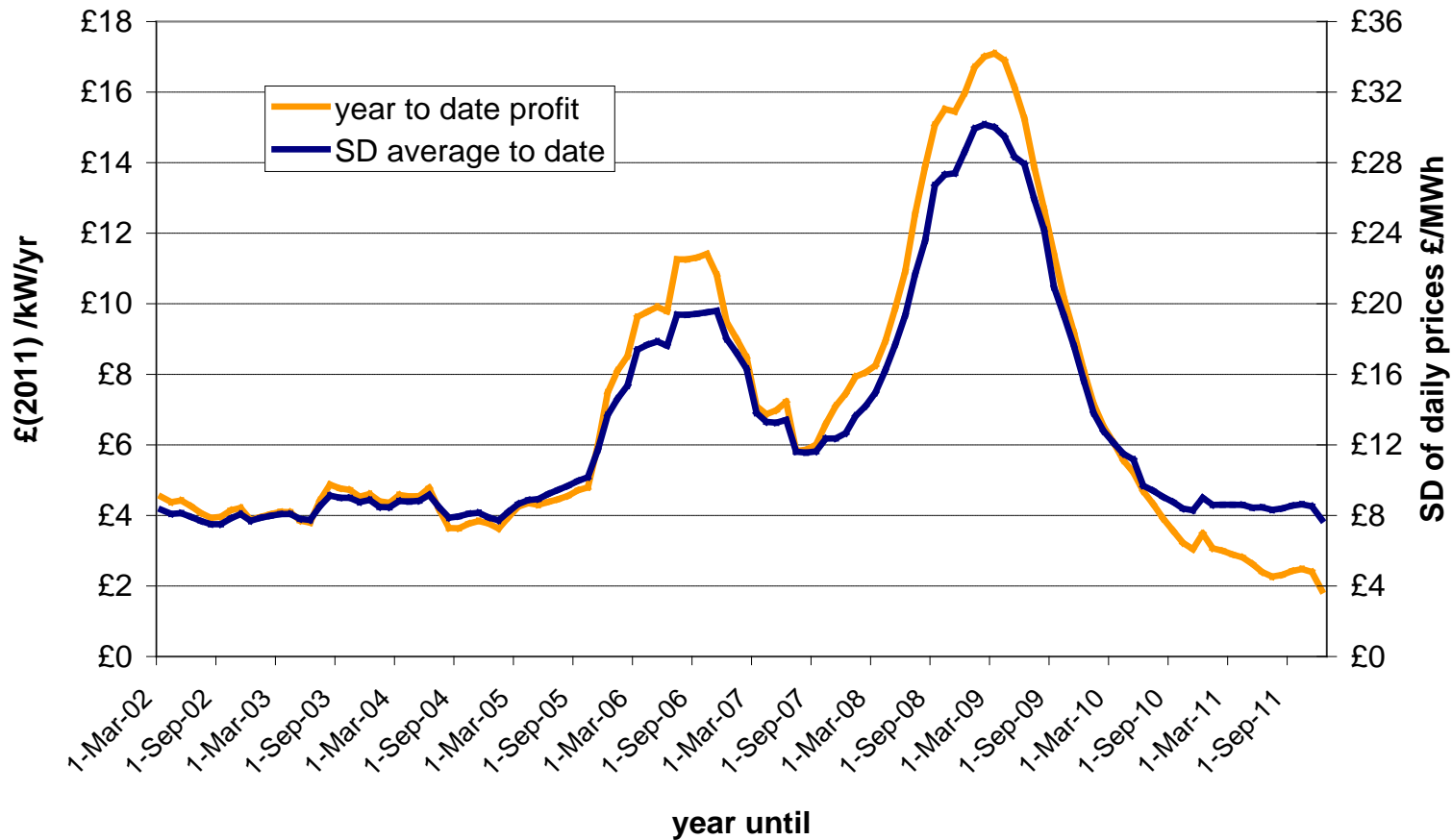
- 20-25% losses
- Main cost is depreciation: 60% DoD: 3000 kWh/kWh capacity **\$10/MWh cycle cost?**
 - Much cheaper for high frequency modest discharge

EES overhead costs

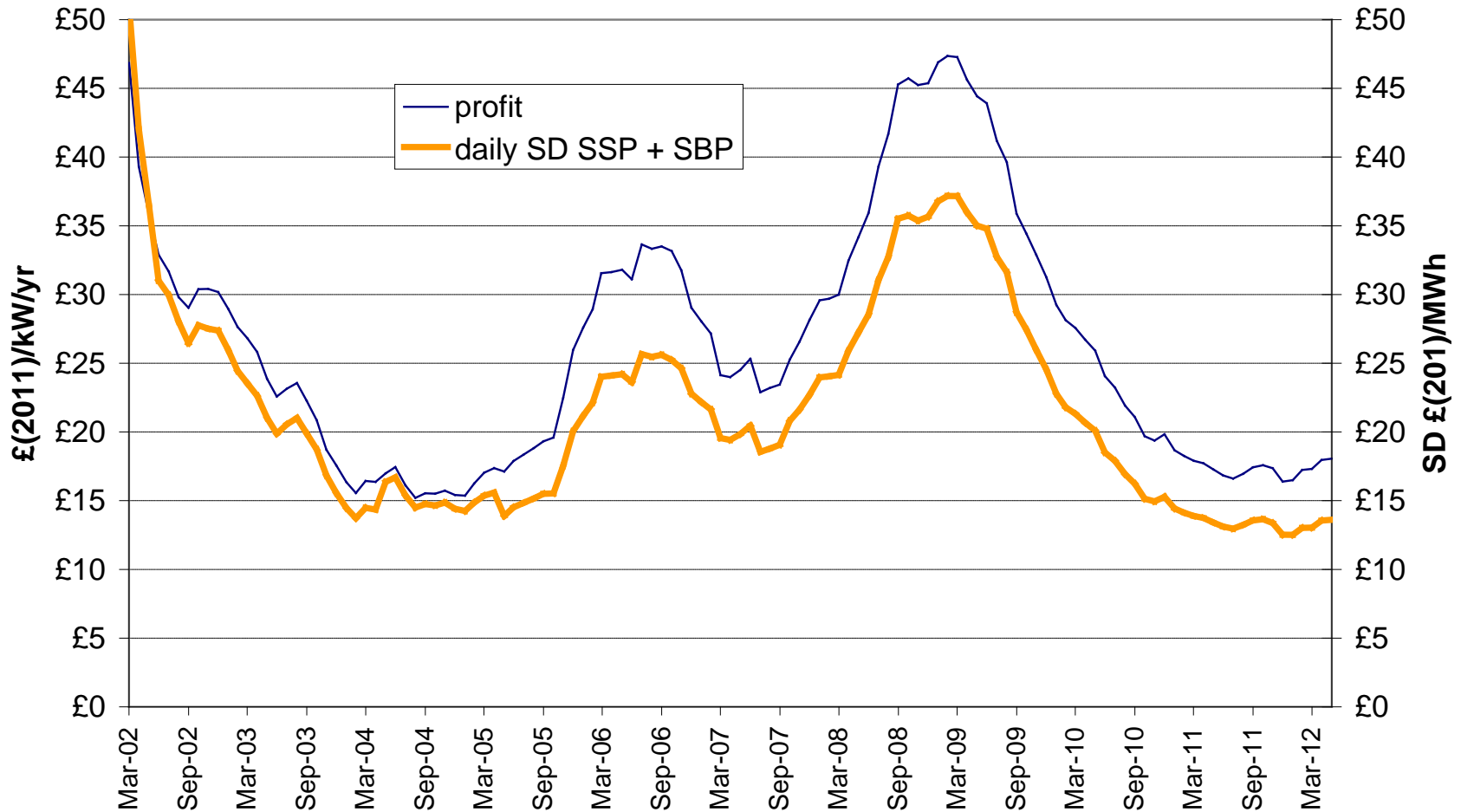
		cost/kWh capacity	DoD	O&M /kW.yr	cycles/ day	Life yrs.	levelized cost/MWh
Leighton Buzzard Li-ion NOAK		£850	100%	£10	1	9	£251
Leighton Buzzard Li-ion NOAK		£850	75%	£13	2	10	£264
Tesla 2018 Low		\$475	100%	\$15	1	12	\$207
Tesla 2018 High		\$1,050	60%	\$20	2	14	\$323
Li-Ion 2020 Low		\$385	100%	\$15	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

**Annual profit from pumped storage
and SD of daily wholesale spot prices, £2011**

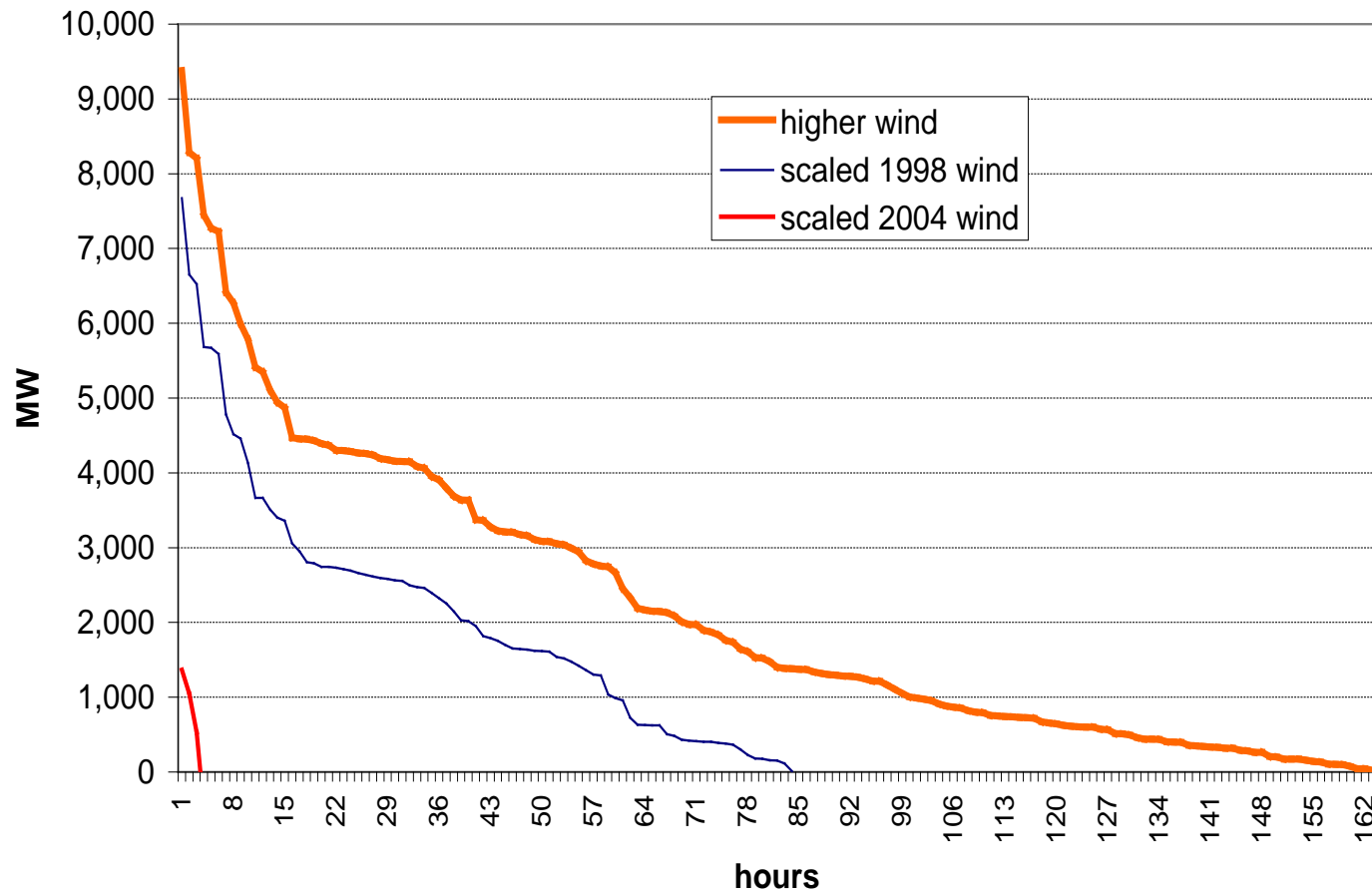


Annual profit trading in Balancing Mechanism and average daily SD of all balancing prices, £2011

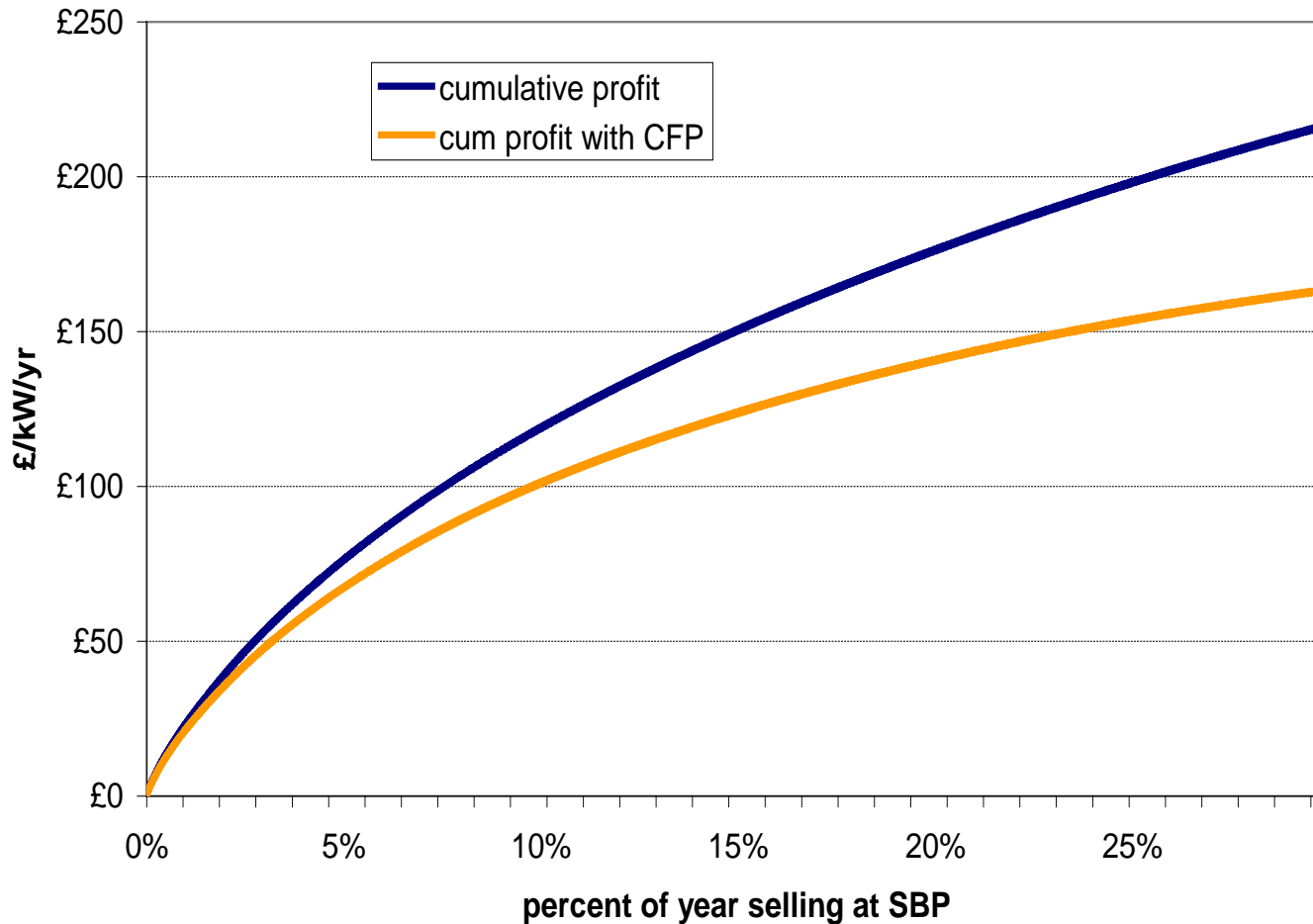


Wind spilled if no export nor storage

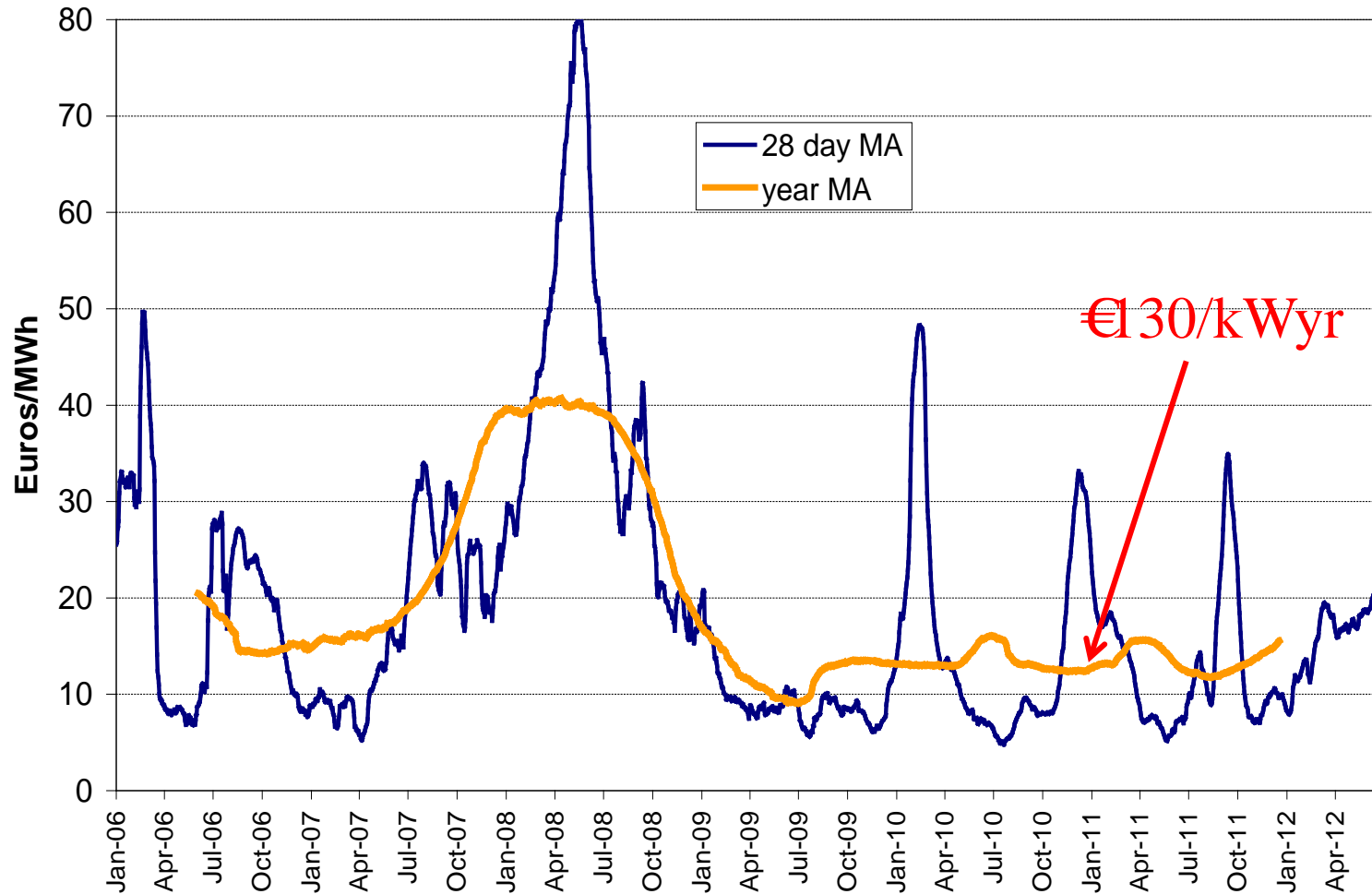
Excess GB supply duration curve projected 2020



Cumulative profit of OCGT selling at SBP 2008



Absolute price differences Norway-Britain



- 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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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