Electronic Supplementary Material (ESI) for Energy & Environmental Science

† Electronic Supplementary Information (ESI): On reducing the energetic and material demands of electrical energy storage

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1 Storage capacity

The amount of storage needed for incorporating increasing amounts of variable resources into electrical grids is a critical yet complicated question. To begin with, the electrical grid, composed of myriad power sources and sinks is conducted as a whole in real-time. Additionally, the number of technologies and practices, their varied and evolving characteristics, and their possible implementations under differing and shifting policy landscapes presents a grossly under-determined problem with several solutions.

Technologies and practices positioned to ensure grid-reliability include flexible conventional generation (natural gas combustion turbines and diesel generation sets), flexible renewable generation (curtailment, hydropower, concentrated solar power (CSP) with thermal storage), flexible load (demand-side management), energy storage, and resource sharing (diversity and transmission). In the future, when greenhouse gas emissions are constrained, flexible generation will need to be achieved using low carbon energy supplies.

Studies have made efforts to determine the amount of renewable generation an electrical grid can support by bundling these technologies and practices into an abstract resource: grid flexibility, defined as the percentage of generation and load capable of being readily dispatched or halted [1]. Less flexible grids harbor high percentages of so-called baseload generating plants such as nuclear, coal and natural gas combined cycle plants. The amount of energy storage capacity required will depend firstly on grid flexibility and, secondly, on attributes of the renewable generation. The amount, type, mix and degree of supply correlation affects how well supply satisfies demand.

Given this tremendous uncertainty and complexity in firming grid-scale renewable generation, estimates for the amount of energy storage required to firm renewable resources encompass a wide range a values that are described in several different ways: power capacity (e.g. GW), energy capacity (TWh), discharge time (hours), fraction of renewable generation that is stored during a day or year, and fraction of total generation that is stored during a day or year. We use fraction of average daily demand as referred to in the literature as both a percentage and/or as number of hours (e.g. 50% is equivalent to 12 hours) [2]. Actual energy terms are obtained by multiplying the percentage by average daily demand or the number of hours by average daily power draw. The average daily power and energy demands at scales ranging from a household to the world are shown in table 1.

Table 1 Average daily electrical energy demand and power demand

	power	energy
World[a]	2.1 TW	50.6 TWh
USA[b]	0.43 TW	10.2 TWh
China[c]	0.53 TW	12.6 TWh
San Francisco[d]	633 MW	15.2 GWh
EE* Hospital[e]	568 kW	13.6 MWh
EE Office Bldg[f]	131 kW	3.14 MWh
EE household[g]	0.33 kW	8 kWh

*Energy Efficient (EE). (*Values obtained from*: [a,b,c] 3, [d] 4, [e] 5, [f] 6, [g] 7)

In this study we assume a capacity range informed by several estimates for storage required in future electrical grids incorporating high percentages of variable generation sources. Table 2 lists energy storage capacities available today. Firstly, today the United States stores $\sim 0.15\%$ of its electricity[1]. Secondly, MacKay et al., 2009 [9] argues we need a store of roughly one day of average generation to cope with weather lulls that commonly last 2 to 5 days. Thirdly, using a similarly heuristic argument, Wadia et al., 2011 [10] assume a long-term global storage capacity goal of one day's worth of generation. Fourthly, Denholm and Hand, 2011 [2] employed a dispatch model to specifically examine changes in electrical grids required to incorporate high percentages of variable generation. They found that for penetration levels up to 80% increasing amounts of storage from 4 to 24 hours reduced curtailment and increased wind capacity factors but with diminishing returns beginning at about 8 hours. Finally, Hand et al., 2012 [11] incorporated these results in a large scale renewable integration study that explored multiple integration options. Though this study does not explicitly state

[1] assuming PHS dominates annual grid storage in 2008 [8]; 6.3 TWh [PHS] / (6.3 TWh [PHS] + 4119.3 TWh [Generation-PHS]) = 0.0015

the optimal storage energy capacity, it identifies a need for 80 to 131 GW of storage power capacity in addition to the 21 GW that exist in the United States with a discharge time of 8 to 15 hours. Assuming this study's scenario dependent annual electricity demand of 2920 to 5100 TWh, then these three variables yield an annual energy storage to energy demand percentage of 5.8 to 21.2%[12]. Table 2 lists present day storage capacity for technologies considered in this study.

Table 2 2011 global storage capacity

technology	power (MW)	energy (GWh)
Li-Ion	$\sim 20^{[a]}$	$0.06^{[g]}$
NaS	$365.3^{[b]}$	$2.191^{[h,i]}$
PbA	$\sim 1,800,000^{[c]}$	$400^{[c]}$
Flow (VRB, ZnBr)	$3^{[a]}$	$0.024^{[j]}$
CAES	$400^{[d]}(650^{[e,f]})$	$3.73^{[d]}$
PHS	$129,000^{[a]}$	$102^{[k]}$

(*Source*: [a] 15, [b] 13, [c]assuming total car batteries worldwide (1 billion) each 10 kg with practical power and energy densities of 180 W/kg and 40 Wh/kg yields 1.8T W and 0.4 TWh of capacity, [d] 16, [e] 17, [f] 18,[g]assuming 3 hr storage, [h]assuming NGK modules[15] with 6 hr discharge, [j]assuming PacifiCorp module[15] with 8 hr discharge, [k]In 2008, USA had 21.5 GW PHS capacity that delivered 6,288 GWh of energy[8]. This yields a capacity factor of 3.33% or $\sim$ 48 min per day. Assuming PHS worldwide operates in kind, 129 GW $\times$ 0.033 $\times$ 24 hr = 102 GWh.

2 Spatial Footprint

A third physical limit energy storage may face is the amount of space it occupies. Several studies and Department of Energy reports identify specific and volumetric energy density as a key research directive[19,20]. We calculate the spatial footprint of storage technologies by simply multiplying their volumetric energy density by an assumed height and a desired amount of energy storage.

Figure 1A shows the volumetric and specific energy densities for several storage technologies. Because size and mass are critically important for devices ranging from cellular phones to electric vehicles, these plots are common in the energy storage industry and have a unique name: Ragone plots.

Using the practical volumetric energy density data, we calculate the spatial footprint required to supply a day's worth of energy storage for scales ranging from an energy efficient household to the world's land surface area. Figure 1B shows that all storage technologies would occupy a small fraction of the footprint of buildings and geographic locations that they support. Even energy dense buildings including hospitals could house storage technologies within their perimeter.

References

[1] P. Denholm and R. M. Margolis, *Energy Policy*, 2007, **35**, 2852–2861.

[2] P. Denholm and M. Hand, *Energy Policy*, 2011, **39**, 1817–1830.

[3] CIA, *World Fact Book*, 2012, `https://www.cia.gov/library/publications/the-world-factbook/\#`.

[4] CEC, *CA.gov Energy Consumption Data Management System*, California energy commission technical report, 2010.

[5] Mahlum, *Integrated Sustainability in Healthcare*, 2012, 7.

[6] B. Dixon-smith, A. Kwok, R. Satterlee, F. Pincheira and W. Howekamp, *Comparison of Y2E2 Occupancy, Comfort, and Energy Audit to Building Objectives*, Stanford's Center for Integrated Facility Engineering Technical Report December, 2011.

[7] EIA, *2005 Residential Energy Consumption Survey*, Energy information administration technical report, 2005.

[8] EIA, *Electric Power Monthly April 2012*, U.S. Energy Information Adminsitration Technical Report April, 2012.

[9] D. MacKay, *Sustainable Energy - without the hot air*, UIT Cambridge Limited, Cambridge, illustrate edn, 2009, vol. 78, p. 384.

[10] C. Wadia, P. Albertus and V. Srinivasan, *Journal of Power Sources*, 2011, **196**, 1593–1598.

[11] M. Hand, S. Baldwin, E. DeMeo, J. Reilly, T. Mai, D. Arent, G. Porro, M. Meshek and D. Sandor, *NREL TP-6A20-52409*, 2012.

[12] C. Augustine, R. Bain, J. Chapman, P. Denholm, E. Drury, D. Hall, E. Lantz, R. Margolis, R. Thresher, D. Sandor, N. Bishop, S. Brown, G. Cada, F. Felker, S. Fernandez, A. Goodrich, G. Hagerman, S. Heath, G.; ONeil and K. Paquette, *NREL TP-6A20-52409-2*, 2012, **2**, year.

[13] T. Reddy and D. Linden, *Linden's Handbook of Batteries*, McGraw-Hill Prof Med/Tech, 4th edn, 2010, p. 1200.

[14] M. Semadeni, *Encyclopedia of Energy*, 2004, **5**, 719–738.

[15] D. Rastler, *Electricity Energy Storage Technology Options: A White Paper Primer on Applications, Costs, and Benefits*, Electric power reseach institute technical report, 2010.

[16] S. Succar, *Large Energy Storage Systems Handbook*, CRC Press, Boca Raton, FL, 2011, ch. 5, pp. 111–153.

[17] Sandia National Laboratory, *American Recovery and Reinvestment Act: Energy Storage Demonstrations*, Sandia national laboratory energy storage systems technical report, 2011.

[18] RWE, *Adele adiabatic compressed air energy storage for electricity supply*, Rwe power ag technical report, 2010.

[19] J. Goodenough and M. Buchanan, *Basic research needs for electrical energy storage*, U.s. department of energy, office of basic energy science technical report, 2007.

[20] M. Armand and J.-M. Tarascon, *Nature*, 2008, **451**, 652–657.

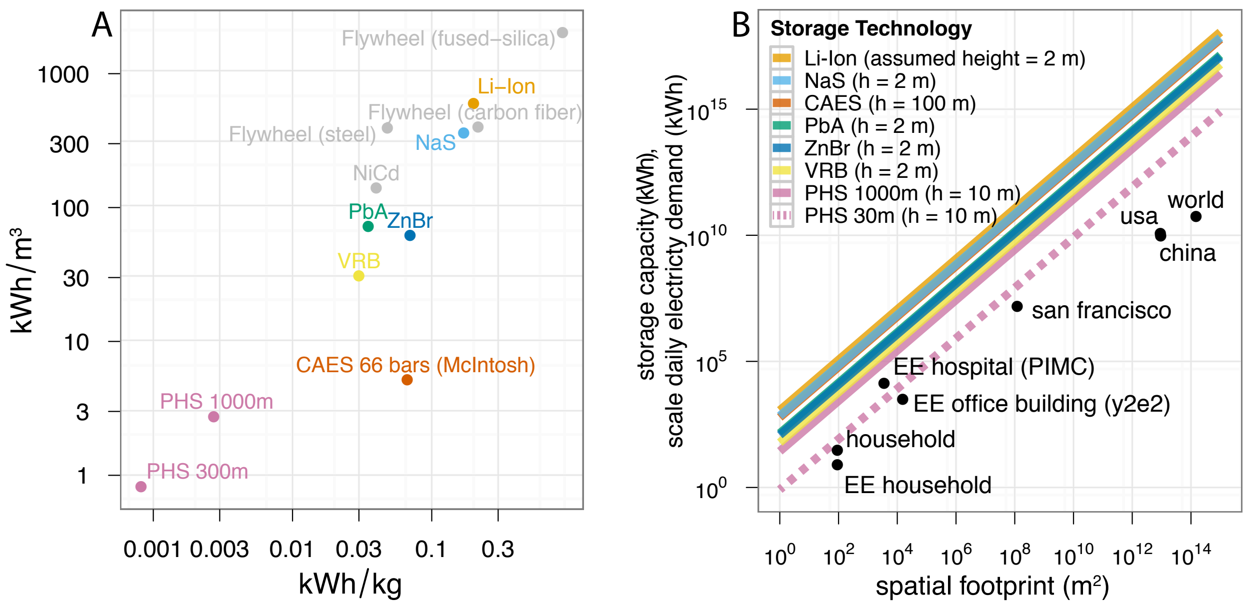

Figure 1 (A) A plot comparing volumetric and specific energy densities for energy storage technologies. Technologies considered for large-scale energy storage have labels in color (data obtained for PHS and CAES are calculated, battery data from [13], flywheel data from [14]). (B) The spatial footprint for energy storage technologies as a function of energy storage capacity. Technologies are plotted as solid lines with color corresponding to technology type. Various average daily electric energy demand scales and their spatial footprints are plotted as circles. Storage technologies that occupy smaller fractions of particular demands spatial footprint are more desirable for buildings.