Electronic Supplementary Material (ESI) for Energy & Environmental Science.

Can we afford storage? A dynamic net energy analysis of renewable electricity generation firmed by energy storage† - Supporting Information

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1 Energy payback time (EPBT) and industry growth

1.1 Inputs and output from a single energy system and an energy industry

Figure 1 depicts energy flows into and out of a single energy production device or system, e.g. a solar photovoltaic (PV) system or a wind farm. Construction begins at time, $t - t_c$, requiring a total energy input to construction of E_{con}, assumed to flow at a constant rate, $\dot{E}_{con} = \frac{E_{con}}{t_c}$. Once the project starts producing energy it is assumed to produce a constant gross flow of energy at rate $\dot{E}_g$ over the lifetime t_L. An energy flow, $\dot{E}_{op}$,is required to operate and maintain the system. At the end of the system lifetime, some energy, E_d is required for decommissioning, again assumed to flow at a constant rate, $\dot{E}_d$[1].

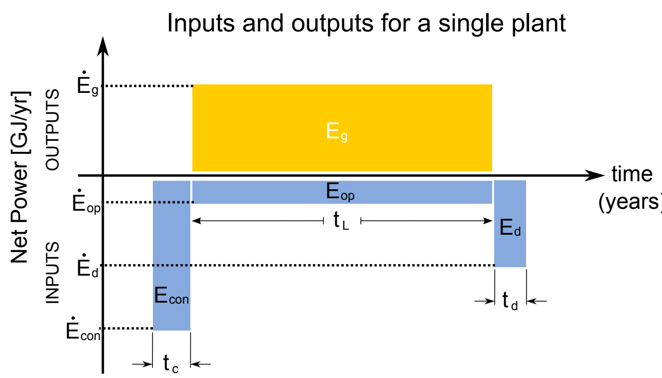

Fig. 1 Energy inputs and outputs to a single energy production system. Energy inputs (blue) are above the horizontal line and energy production (yellow) is shown above the line.

Two metrics used to characterize the scale of energy inputs and outputs at the system level are the *cumulative energy demand* (CED), defined as "the amount of *primary* energy consumed during the life cycle of a product or a service"[2] and the *energy payback time* (EPBT), defined as"the time necessary for an energy technology to generate the equivalent amount of *primary* energy used to produce it"[3]. Turning instead to the industry-scale, as depicted in Figure 2, a rapidly growing industry may deploy new systems before previous deployment has 'paid off' thereby driving the whole industry into an energy deficit. Energy must be imported from *outside* the industry. The term *energy subsidy* is used to define this energy input, to distinguish from the energy investment at the system level. An industry composed of individual systems, each with a positive net energy contribution over their lifetimes, could still run an energy deficit, when growing rapidly.

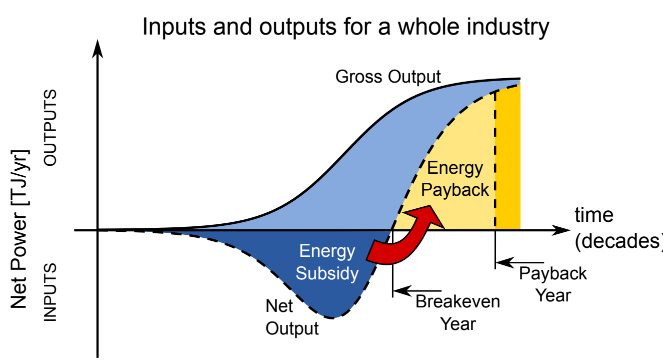

Fig. 2 Energy inputs and outputs for an energy production industry growing asymptotically to some upper limit. Gross output is shown as a bold line, net output is shown with the dashed line.

If either the industry growth rate or the CED of systems being deployed decrease sufficiently, the industry's net energy output will pass through a minimum value, after which the industry may then cross the *breakeven threshold* and thereafter produce a positive net energy output. This crossover happens in the *breakeven year*. After some time, the industry produces enough positive net energy to "pay back" the energy subsidy required for its early growth. The year in which this occurs is termed the *payback year*. The *fractional reinvestment* defines the proportion of annual energy output from the industry is used in manufacture and deployment of new capacity.

1.2 Mapping net energy trajectory

Grimmer (1981) defines the relationship between the *fractional reinvestment*, f [%], the industry growth rate, r [%/yr] and the EPBT [yrs] of plants comprising the industry for a growing energy production industry as[4]

$$f = r\text{EPBT}. \tag{1}$$

Using this relationship, Figure S3 shows the contours of f (sloping diagonal lines) on a log-log plot. A fractional reinvestment of 100% marks the breakeven threshold. Green lines in the bottom left half of the digram represent the positive net energy regime, $f \leq 100\%$, red lines in the top right represent the negative net energy regime.

To make use of the plot, we can choose any two of either the growth rate (left axis), the EPBT (bottom axis), or the fractional reinvestment (diagonal contours). Assuming we have a device technology with an EPBT of 2 yrs and want to limit the fractional investment to 80%, what is the fastest rate at which an industry based on deployment of such devices could grow without energy subsidy? We trace up from the bottom axis at EPBT = 2 yrs until we meet the sloping fractional reinvestment line, f = 80%. We then trace horizontally from this point to meet the vertical axis at a growth rate of 40 %/yr.

Since we know that the current average growth rate of the PV industry is 40%, we can trace horizontally across at this value to discover that, for the PV industry as a whole to be a positive net energy provider (i.e. with a fractional reinvestment of less than 100%), the EPBT must be below 2.5 yrs.

If an industry is running an energy deficit, there are three means by which it may cross the breakeven threshold: (1) reduce the EPBT of system production, i.e. move across the plot horizontally from right to left, (either by reducing the energetic cost of system deployment or increasing the capacity factor achieved by deployed systems) or ; (2) reduce the industry growth rate, i.e. move vertically down the plot or; (3) some combination of (1) and (2).

2 Installed capacity of wind and PV

Installed capacity [GW] for wind and PV between 1990 and 2012 is presented in Table 1. There is a slight disparity between the values displayed in Table 1 and the values used in a previous study[5]. The analysis from that study has been redone on an annual basis using a different dataset disaggregating market share between the different PV technologies[6].

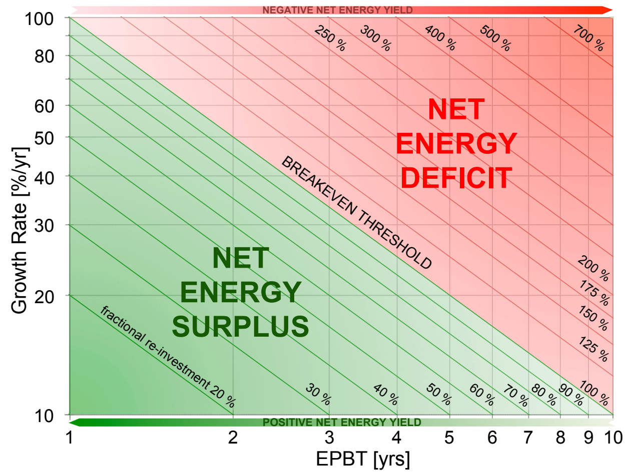

Fig. 3 Fractional reinvestment [%] (diagonal lines) as a function of industry growth rate [%/yr] (vertical axis) and energy payback time (EPBT) [yrs] (horizontal axis). An industry operating in the red region indicates an energy deficit and in the green region indicates an energy surplus.

3 Energetic inputs to energy supply system

3.1 Energetic inputs to energy production

Cumulative electricity demand (CE$_e$D) [kWh$_e$/W$_p$], as defined in[5], for wind and PV technologies is presented in Figure 4. Data is also available in accompanying file Wind PV CED SI.xlsx.

3.2 Energetic inputs to energy storage

CE$_e$D [kWh$_e$/kWh$_s$], as defined in[13], for storage technologies is presented in Figure 5. Justification for the conversion between energetic costs presented as *primary energy equivalent* to *electrical energy equivalent* are discussed in that study. In summary, many energetic inputs to electrochemical storage manufacture and deployment are either currently, or could in future be electrified[14]. Assuming reservoir construction, dam construction and cavern development require primary energy, hypothetically, about 70%, in the case of PHS, and 90% in the case of CAES, of the energetic costs of deployment could be electrified[15].

3.3 Model to track changes in CE$_e$D

This study makes use of the learning curve model presented in[5] to track and project decreases in CE$_e$D of PV systems due to improvements in technology. This model assumes that the CE$_e$D at time t, $c(t)$, is a function of the CE$_e$D at time $t = 0$, c_0,

Table 1 Installed capacity of wind and PV between 1994 disaggregated by technology using data from [5–11]

Year	Installed Capacity [GW]								
	Wind		PV						
	on-shore	off-shore	sc-Si	mc-Si	Ribbon	a-Si	CdTe	CIGS	Other
1990	2.31	-	-	-	-	-	-	-	-
1991	2.71	0.01	-	-	-	-	-	-	-
1992	2.84	0.01	-	-	-	-	-	-	-
1993	3.06	0.01	-	-	-	-	-	-	-
1994	3.04	0.01	-	-	-	-	-	-	-
1995	4.36	0.01	-	-	-	-	-	-	-
1996	5.89	0.03	-	-	-	-	-	-	-
1997	7.27	0.03	-	-	-	-	-	-	-
1998	9.55	0.03	-	-	-	-	-	-	-
1999	14.42	0.03	-	-	-	-	-	-	-
2000	16.43	0.04	0.40	0.52	0.04	0.11	0.01	0.00	0.00
2001	22.80	0.09	0.49	0.64	0.05	0.13	0.01	0.00	0.00
2002	29.60	0.26	0.57	0.75	0.06	0.15	0.01	0.00	0.00
2003	37.15	0.52	0.73	0.98	0.09	0.19	0.01	0.01	0.00
2004	44.77	0.61	0.96	1.30	0.12	0.23	0.01	0.01	0.00
2005	56.51	0.70	1.25	1.82	0.16	0.27	0.03	0.01	0.00
2006	69.94	0.79	1.65	2.43	0.19	0.32	0.04	0.02	0.00
2007	88.98	1.11	2.34	3.38	0.24	0.40	0.07	0.02	0.00
2008	114.23	1.48	3.33	4.44	0.30	0.51	0.13	0.03	0.00
2009	151.36	2.06	5.75	7.04	0.42	0.81	0.41	0.07	0.00
2010	194.59	3.05	8.97	11.06	0.55	1.24	0.94	0.14	0.00
2011	233.92	4.12	14.62	18.87	0.76	2.28	2.45	0.41	0.13
2012	277.02	5.41	20.24	26.13	0.92	3.01	4.48	0.64	0.20

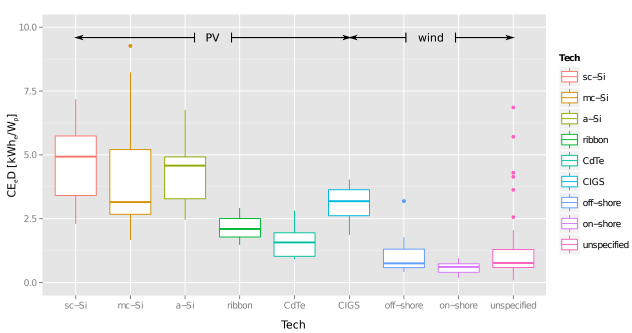

Fig. 4 Distribution in cumulative electricity demand (CE$_e$D) [kWh$_e$/W$_p$] across all of the studies in the meta-analysis for each of the PV and Wind technologies. Data comes from [5,12]

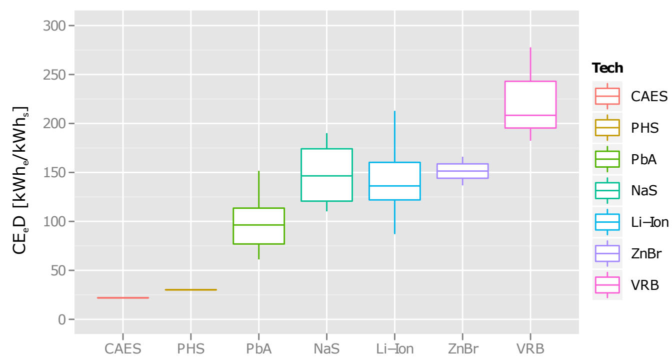

Fig. 5 Distribution in cumulative electricity demand (CE$_e$D) [kWh$_e$/kWh$_e$] across all of the studies in the meta-analysis for each of the storage technologies.

and the cumulative production of the technology (represented by the installed capacity K) at both time t, $K(t)$, and $t = 0$, K_0, such that:

$$c(t) = c_0 \left(\frac{K(t)}{K_0} \right)^{\lambda} \tag{2}$$

where λ defines the rate of decrease in CE$_e$D due to technology improvements and is assumed to remain constant. The learning rate is defined as the percent decrease in cost (either energetic or financial) for a doubling in cumulative production, for example, a value of $\lambda = -0.2$ is equivalent to a learning rate of $1 - 2^{-0.152} = 10\%$. Values for λ, learning rates and initial CE$_e$D, c_0, for the different wind and PV technologies are presented in Table 2. K_0 has a value of 1 MW of cumulative production. Experience curves are plotted in Figure 6.

4 Storage requirement

4.1 Storage for wind

We here carry out a thought exercise in which we must continually provide the average daily power output, W_{avg}, from an intermittent generation technology with peak capacity W_p via

Table 2 Value of λ for the wind and PV technologies being modelled taken from[5].

Technology	λ [dmnl]	Learning Rate [%]	Initial CE_eD , c_0 [kWh_e/W_p]
wind: onshore	-0.065[a]	4.4	1.6[a]
wind: offshore	-0.065[a]	4.4	1.6[a]
PV: sc-Si	-0.304	19.0	42.7
PV: mc-Si	-0.366	22.4	61.0
PV: a-Si	-0.235	15.0	12.7
PV: ribbon	-0.215	13.8	5.4
PV: CdTe	-0.275	17.4	7.6
PV: CIGS	-0.281	17.7	7.1

[a] Same value was assumed for both onshore and offshore wind

[b] Value was assumed from a-Si due to lack of data

[c] Value was assumed from CdTe due to lack of data

images/Learning_curves.pdf

Fig. 6 Learning curves for the wind and PV industries and each of the individual PV technologies.

the use of storage. The aim is to demonstrate the relationship between the storage needed and the capacity factor, $\kappa = \frac{W_{avg}}{W_p}$. We will initially look at the case for 24 hours and then turn to the more general case.

We assume that in each twenty-four hour period, a generation technology is supplied with enough energy flow (either wind or sunlight) to deliver 24 hours of average electrical power output, for example at wind turbine with capacity factor $\kappa_{PV} = 0.25$ would receive 0.25 × 24 = 6 Wh_e/W_p. In a 'worst-case' scenario this energy supply would arrive in one period of time, i.e. a block of 6 hours in the case of our wind turbine, at the rated capacity of the generation, i.e. 1 W_e/W_p. Since a steady supply of 0.25 W_e/W_p is being delivered to the grid, the remaining 0.75 W_e/W_p must be stored for a total of 0.75 × 6 = 4.5 Wh_s/W_p. When the generation is no longer supplying electricity, the storage is called upon to deliver electricity to the grid.

The situation is presented in Figures 7. The energy supplied by generation, E_{out}, is represented by the blue rectangle, the energy demand, E_d, is represented by the red rectangle. The area of the blue rectangle must equal the area of the red rectangle. There is a proportional relationship between the value of W_{avg} and t—as t increases, so does W_{avg}. In this case for a 24 hour period, if $t = 24$ hrs then $W_{avg} = W_p$. We may state that:

$$tW_p = 24W_{avg} \Longrightarrow \frac{W_{avg}}{W_p} = \kappa = \frac{t}{24} \qquad (3)$$

In Figure 8 we see the effect of holding W_{avg} constant at 1W and setting t to have values ranging from 1 hr—with an associated capacity factor of $\kappa = 1/24$—up to t = 12 hours—with associated capacity factor of $\kappa = 12/24 = 1/2$. The value of W_p varies inversely with the value of t. We assume that any generation not sent directly to the grid is put into storage (to be used when the generation is no longer supplying electricity). This amount of power, $W_p - W_{avg}$, must be stored for the time t, such that the storage required, E_s, is:

$$E_s = t\,(W_p - W_{avg}) = 24\kappa\,(W_p - W_{avg}) \qquad (4)$$

The relationship between κ and E_s is shown as the sloping blue line in Figure 9. Normalizing the energy storage, E_s, with respect to peak capacity, W_p, we obtain:

$$\frac{E_s}{W_p} = 24\kappa\left(\frac{W_p}{W_p} - \frac{W_{avg}}{W_p}\right) = 24\kappa(1-\kappa) \qquad (5)$$

We find that the storage requirement per unit of peak capacity, $\frac{E_s}{W_p}$ is a peaking function of the capacity factor as represented by the red dashed line in Figure 9.

Extending the analysis to assume that the storage may have to cover any period of time, τ, for example up to three days without generation (as has been suggested by some authors[16]), by again assuming that the generation arrives in one period at full capacity, W_p we obtain:

$$tW_p = \tau W_{avg} \Longrightarrow t = \tau\frac{W_{avg}}{W_p} = 72\kappa \qquad (6)$$

Now, the amount of energy that must be stored, E_s may be defined:

$$E_s = t(W_p - W_{avg}) = \tau\kappa(W_p - W_{avg}) \tag{7}$$

Normalizing energy storage to a per unit peak capacity we obtain:

$$\frac{E_s}{W_p} = \tau\kappa(1-\kappa) \tag{8}$$

The storage requirement [Wh/W$_p$] is plotted as a function of capacity factor [%] for both 24 hours (blue line) and 72 hours (red line) of power delivery in Figure 10. The storage requirement reaches a maximum value at a capacity factor of 50% of 6 Wh$_s$/W$_p$ and 18 Wh$_s$/W$_p$ for the 24 hour and 72 hour scenarios, respectively. In order to ensure 72 hours of power delivery at average power output at our assumed wind capacity factor of 25 % requires 12.75 Wh$_s$/W$_p$ of storage.

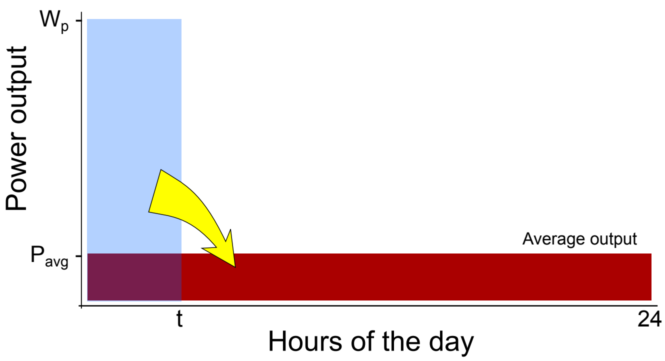

Fig. 7 Power output (blue) and power demand (red) over the course of a 24 hour period. Power output is supplied at the rated capacity, W_p, for some number of hours, t.

4.2 Storage for PV

We now approximate the energy storage capacity needed to support a PV system. The solar case is different from that for wind, since the profile of power production, W_{out}, is dependent on the solar irradiance, as shown in Figure 11. An inexact, approximate shape for the solar profile may be represented by a simple cosine function of t, such that:

$$W_{out} = W_p \cos\left(\frac{W_p \pi}{12} t\right) \tag{9}$$

where the units of t are hrs. The integral of this curve, E_{out}, must equal the total energy delivered, E_d, therefore:

$$E_{out} = W_p \int_{t_1}^{t_2} \cos\left(\frac{W_p \pi}{12} t\right) dt = E_d = 24W_{avg} \tag{10}$$

The amount of energy that must be stored, E_s, may be calculated as:

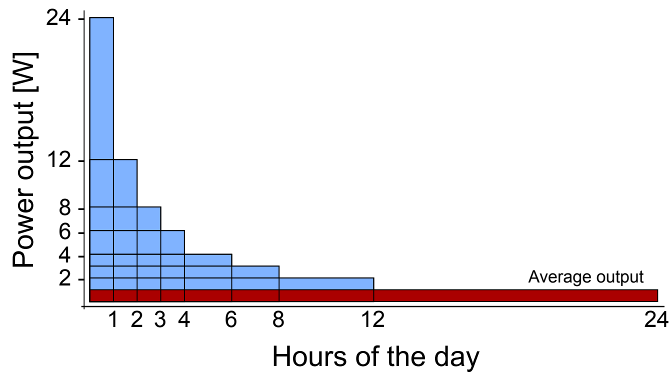

Fig. 8 Power output (blue) and power demand (red) over the course of a 24 hour period. Average power output, W_{avg} is kept constant at 1 Wh. The energy that must be supplied over a 24 hour period is 24 Wh, which may be supplied by a variety of systems with differing peak capacities, W_p, and capacity factors, κ, operating for a variety of lengths of time, t.

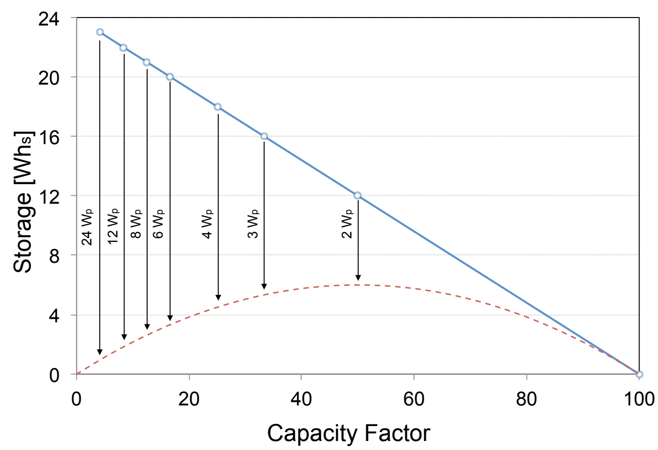

Fig. 9 Storage requirement [Wh] plotted as a function of capacity factor [%] for 24 hours of power delivery. The storage requirement is a decreasing function of capacity factor (blue line) which when normalized to peak capacity, W_p, may be represented by the red dashed line.

$$E_s = W_p \int_{t_a}^{t_b} \left(\cos\left(\frac{W_p \pi}{12} t\right) - \frac{W_{avg}}{W_p}\right) dt \tag{11}$$

We may calculate t_a and t_b by finding the value of t when $\cos\left(\frac{W_p \pi}{12} t\right) - \frac{W_{avg}}{W_p} = 0$, such that:

$$t_a = \frac{12}{W_p \pi} \arccos(\kappa) \tag{12}$$

and

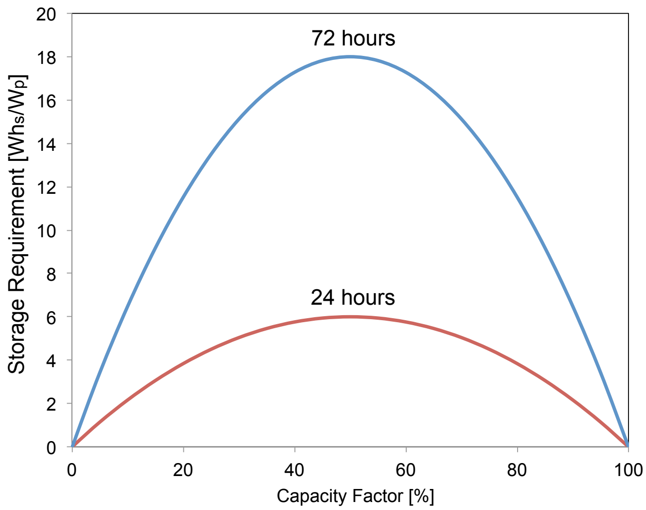

Fig. 10 Storage requirement [Wh/W$_p$] plotted as a function of capacity factor [%] for both 24 hours (red line) and 72 hours (blue line) of power delivery. The storage requirement reaches a maximum value at a capacity factor of 50%.

$$t_b = -t_a \tag{13}$$

In Figure 12 we see the effect of holding W_{avg} constant and varying t. As before, the value of W_p varies inversely with the value of t. Using a similar method as before we can determine the amount of storage required to deliver 24 hours at 1 W both in absolute terms [Wh$_s$] and per capacity [Wh$_s$/W$_p$] basis for a range of capacity factors, as shown in Figure 13.

In analytic terms the per capacity storage requirement, $\frac{E_s}{W_p}$ may be defined:

$$\frac{E_s}{W_p} = 12\kappa\left[\sin\left(\arccos(\kappa)\right) - \sin\left(\arccos(-\kappa)\right) - 2\kappa \arccos(\kappa)\right] \tag{14}$$

This function peaks at a value of $\kappa = 0.4$ at a value of 4.35 Wh$_s$/W$_p$. As before, we may scale this storage requirement to deliver 72 hours of power delivery, as shown in Figure 14. In order to ensure 72 hours of average power output for our assumed PV capacity factor of 11.5 % requires 6.84 Wh$_s$/W$_p$ of storage. To ensure 24 hours of average power output requires 2.28 Wh$_s$/W$_p$ of storage.

4.3 Effect of depth of discharge and round-trip efficiency

The preceding argument assumes that the storage technology is charged and discharged to its full capacity and that the storage technology is able to deliver the full amount of electricity

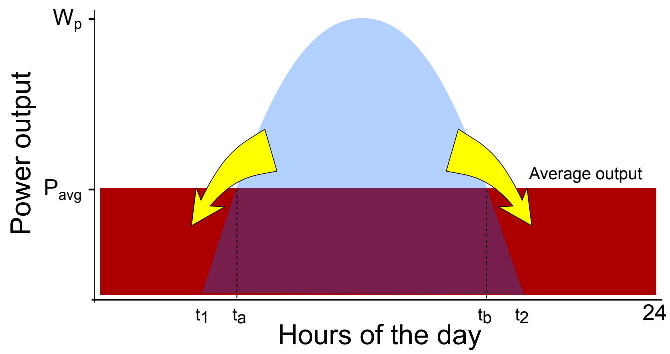

Fig. 11 Power output for a solar generator (blue) and power demand (red) over the course of a 24 hour period. The red and blue areas must be equal.

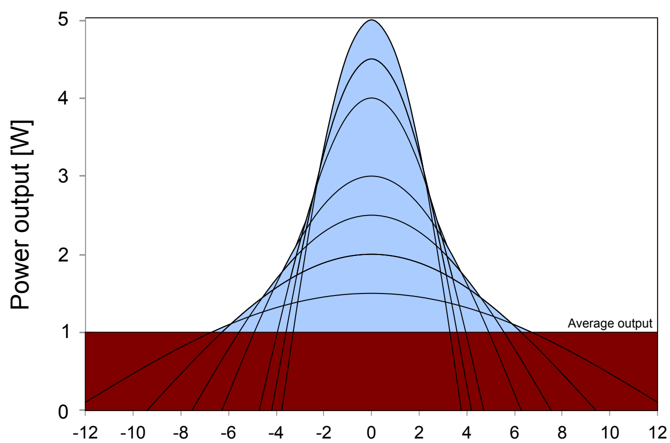

Fig. 12 Power output (blue) and power demand (red) over the course of a 24 hour period. Average power output, W_{avg} is kept constant at 1 Wh. The energy that must be supplied over a 24 hour period is 24 Wh, which may be supplied by a variety of systems with differing peak capacities, W_p, and capacity factors, κ, operating for a variety of lengths of time, t.

delivered to it by the generation, i.e. that the round-trip efficiency is 100%. In reality, storage technologies are not 100% efficient, nor do storage operators discharge them to their full capacity but to some fraction, known as *depth of discharge*. There is an inverse relationship between storage cycle life—how many cycle the storage technology can perform over its full lifetime—and the depth of discharge [17], i.e. a greater depth of discharge gives a shorter storage lifetime.

Including depth of discharge, D, into our results from the previous sections, we find that the per unit peak capacity storage requirement becomes:

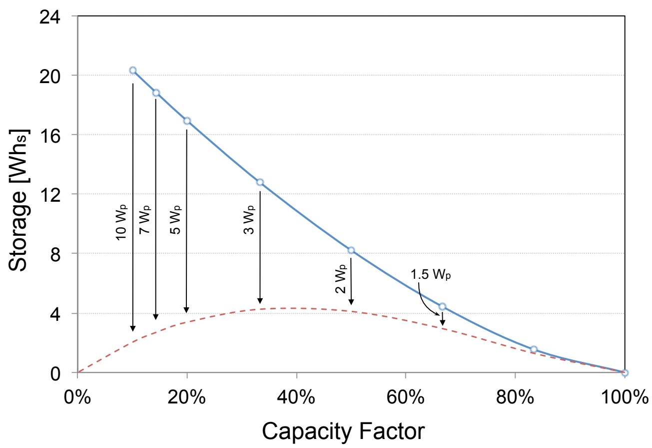

Fig. 13 Storage requirement [Wh] plotted as a function of capacity factor [%] for 24 hours of power delivery at W_{avg} = 1 W. The storage requirement is a decreasing function of capacity factor (blue line) which when normalized to peak capacity, W_p, may be represented by the red dashed line. We have here illustrated the plot with $t_{midday} = 0$ to match with the function $\cos(t)$ function that we are using for the analysis.

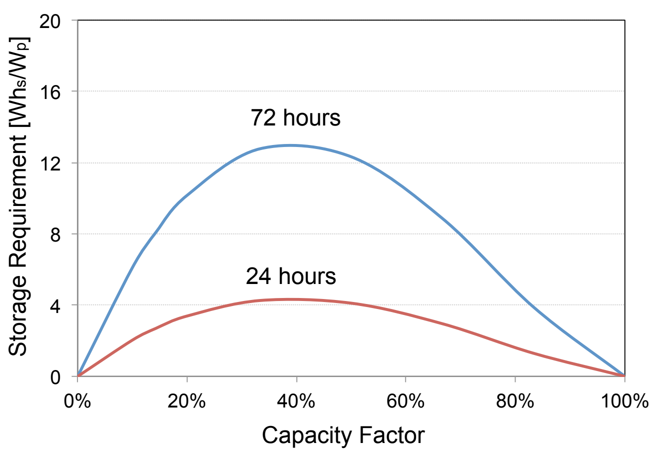

Fig. 14 Storage requirement [Wh/W_p] plotted as a function of capacity factor [%] for both 24 hours (red line) and 72 hours (blue line) of power delivery. The storage requirement reaches a maximum value at a capacity factor of 50%.

$$\text{Wind}: \frac{E_s}{W_p} = \frac{\tau}{D}\kappa(1-\kappa) \tag{15}$$

$$\text{PV}: \frac{E_s}{W_p} = \frac{\tau}{2D}\kappa\left[\sin\left(\arccos(\kappa)\right) - \sin\left(\arccos(-\kappa)\right) - 2\kappa\arccos(\kappa)\right] \tag{16}$$

Clearly, unless a storage technology is 100% efficient, not all of the electricity put into storage will be delivered to the grid. In reality, storage technologies have a range of efficiencies, η_s, from 65-95% [17]. In order for the storage technology to deliver electricity for the full $\tau - t$ hours that the generation technology is not operating, it must deliver at a rate of ηW_{avg} in order to account for round-trip efficiency losses.

5 Methodology

5.1 Deployment of storage

In this analysis we study the effects of a policy that storage is required to firm intermittent and variable resources by being able to store (or conversely to supply) p hours of average power output, i.e. the capacity factor κ [kW$_e$/W$_p$]. The cost of energy storage will depend on the type of storage we are using. The vector $\vec{\alpha}$ [dmnl] defines the allocation of each storage type. For example, if we are allocating all storage technologies equally then:

$$\vec{\alpha}_{all} = \begin{bmatrix} \alpha_{CAES} \\ \alpha_{PHS} \\ \alpha_{Li-Ion} \\ \alpha_{NaS} \\ \alpha_{ZnBr} \\ \alpha_{VRB} \\ \alpha_{PbA} \end{bmatrix} = \begin{bmatrix} 1/7 \\ 1/7 \\ 1/7 \\ 1/7 \\ 1/7 \\ 1/7 \\ 1/7 \end{bmatrix} \tag{17}$$

Similarly, for geologic storage technologies:

$$\vec{\alpha}^{\mathrm{T}}_{geo} = \left[\frac{1}{2}, \frac{1}{2}, 0, 0, 0, 0, 0\right] \tag{18}$$

and for electrochemical storage technologies:

$$\vec{\alpha}^{\mathrm{T}}_{batt} = \left[0, 0, \frac{1}{5}, \frac{1}{5}, \frac{1}{5}, \frac{1}{5}, \frac{1}{5}\right] \tag{19}$$

The vector $\vec{\varepsilon}$ [kWh$_e$/kWh$_s$] defines the median energy cost [kWh$_e$] per unit of storage capacity [kWh$_s$] of each storage type as shown in Figure 5, such that:

$$\vec{\varepsilon} = \begin{bmatrix} \varepsilon_{CAES} \\ \varepsilon_{PHS} \\ \varepsilon_{Li-Ion} \\ \varepsilon_{NaS} \\ \varepsilon_{ZnBr} \\ \varepsilon_{VRB} \\ \varepsilon_{PbA} \end{bmatrix} = \begin{bmatrix} 22 \\ 30 \\ 99 \\ 148 \\ 143 \\ 151 \\ 223 \end{bmatrix} \mathrm{kWh}_e/\mathrm{kWh}_s \tag{20}$$

We calculate the per unit storage capacity energy cost of deploying storage by taking the dot product $\vec{\alpha}.\vec{\varepsilon}^{\mathrm{T}}$. Such that:

$$\varepsilon_{all} = \vec{\alpha}_{all}.\vec{\varepsilon} = 117 \mathrm{kWh}_e/\mathrm{kWh}_s \tag{21}$$

Table 3 Storage requirement, $\frac{E_s}{W_p}$ [kWh$_s$/W$_p$], capacity factor, κ [%], and energy cost, c_s [kWh$_e$/W$_p$] for each of the generation-storage technology combinations for 24 hours of storage back-up.

		$\frac{E_s}{W_p}$	$c_{s,all}$	$c_{s,geo}$	$c_{s,batt}$
ε	-		0.117[a]	0.026[a]	0.153[a]
Generation	κ				
Wind	25.0%	4.5	0.51	0.18	0.70
PV	11.5%	2.3	0.26	0.06	0.35

[a] ε has units of $\frac{kWh_e}{Wh_s}$

$$\varepsilon_{geo} = \vec{\alpha}_{geo}.\vec{\varepsilon} = 26\text{kWh}_e/\text{kWh}_s \tag{22}$$

$$\varepsilon_{batt} = \vec{\alpha}_{batt}.\vec{\varepsilon} = 153\text{kWh}_e/\text{kWh}_s \tag{23}$$

Since from equation 8 we know that the amount of storage required per unit of generation capacity, $\frac{E_s}{W_p}$, is a function of the capacity factor, κ, we may calculate the energy cost, c_s [kWh$_e$/W$_p$], of deploying sufficient storage to supply 24 hours of power at W_{avg} for each of the different storage technologies as:

$$c_{wind,all} = \frac{1}{1000}\frac{E_{wind}}{W_p}\vec{\varepsilon}_{all} = 24\vec{\varepsilon}_{all}\kappa(1-\kappa) = 4.5\vec{\varepsilon}_{all} \tag{24}$$

and

$$c_{PV,all} = \frac{1}{1000}\frac{E_{PV}}{W_p}\vec{\varepsilon}_{all} = 2.28\vec{\varepsilon}_{all} \tag{25}$$

Energy cost, c_s for different generation-storage technology combinations is outlined in Table 3. This cost of storage is then added to the cost of deploying the electricity production technology.

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