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† Supplementary Information (SI)–The energetic implications of curtailing versus storing solar- and wind-generated electricity

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1 Introduction

This supplementary information contains a list of terms and variables used in calculating the system scale energetics of storing electrical energy from wind and solar resources (Table 1). We expand our derivation of grid energy intensity and the energy return on investment ratios for energy resources paired with storage. We list and comment on the resource technology and storage technology life cycle assessment (LCA) data used to calculate our results contained in the main text.

2 Expanded derivations of ε_g and $EROI_{grid}$

In this study we employ two ratios taken from net energy analysis: Energy Return on Investment (EROI) and energy intensity[1,2]. Energy quality depends on its form, so even though EROI and energy intensity are dimensionless we define them in terms of electrical energy. EROI ratios follow our intuition that bigger numbers are better; we use EROI on the axes of plots contained in our main text. We find energy intensity ratios to be less cumbersome in deriving the energetics of generation resources paired with storage; we use energy intensity ratios to build our theoretical framework.

For generation technologies, energy intensity, ε_r, is a ratio of the amount of electrical energy investment per *unit* of electrical energy return. This ratio is an average over the entire life of a technology. For energy generation technologies (wind turbines, solar PV), we obtained energy intensity values from the literature as detailed in section (4).

For storage technologies, the energy returned–that is, the electrical energy withdrawn [*e.g.* kWh]–depends on the total number of charge-discharge cycles, λ [# cycles], the fractional depth-of-discharge, D, that allows λ cycles to be achieved, and the round-trip AC-AC efficiency of the technology, η [*e.g.* kWh_{out}/kWh_{in}]. As such, a storage energy intensity is defined as

$$\varepsilon_s = \frac{\epsilon_e}{\lambda \eta D} \tag{1}$$

where ϵ_e is the embodied electrical energy per unit of electrical energy storage capacity.

Consider a simple power grid with a renewable resource acquisition technology like wind or PV with energy intensity ε_r and a storage technology with an energy intensity ε_s. A fraction of the energy passes through storage, ϕ and the remaining energy, $(1-\phi)$, directly powers the grid. Figure 1 shows a diagram of the energy inputs and outs of this power grid.

Starting at the resource, ε_r units of electrical energy are embodied per unit of electrical energy generated. This unit is then partitioned. ϕ goes into storage and $(1-\phi)$ goes directly to the power grid. The per cycle energy input into the storage device,

$$E_{in_s} = \frac{\phi \epsilon_e}{\lambda D}, \tag{2}$$

depends on the embodied electrical energy per unit electric storage capacity of the device, ϵ_e, the devices depth-of-discharge, D, and how many cycles ϵ_e is divided among, λ. Note E_{in_s} to storage is scaled by ϕ. This means that

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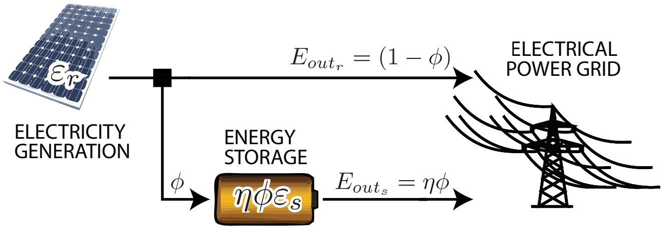

Figure 1 A schematic of an renewable electricity generation technology and energy storage system delivering electrical energy to the power grid. Terms within technologies are the energy inputs per unit output. Flow lines depict electricity outputs.

storage is used in an optimum fashion and that precisely the storage capacity required is the storage capacity built. Casting E_{in_s} in terms of ε_s,

$$E_{in_s} = \phi\eta\varepsilon_s. \tag{3}$$

The fraction of energy that enters storage ϕ is reduced by the round-trip AC-AC efficiency of the storage device and exits storage as $E_{out_s} = \eta\phi$. At the power grid we sum the energy inputs for the fraction, $(1-\phi)$, that goes directly to the grid and the fraction that passes through storage, ϕ. The energy inputs are divided by the energy outputs to obtain the system wide energy intensity, ε_g. The energy inputs are

$$E_{in_g} = \varepsilon_r + \phi\eta\varepsilon_s. \tag{4}$$

The sum of energy outputs directly from generation and from storage are

$$E_{out_g} = (1-\phi) + \eta\phi. \tag{5}$$

Therefore ε_g is

$$\varepsilon_g = \frac{E_{in_g}}{E_{out_g}} = \frac{\varepsilon_r + \phi\eta\varepsilon_s}{1-\phi+\eta\phi}. \tag{6}$$

2.0.1 In terms of EROI

In the main text, $EROI$, $ESOI_e$ and $EROI_{grid}$ are used to build the axes and plot lines of figures 3, 4 and 5. These figures show three important results: combinations of $EROI$, $ESOI_e$ and ϕ that lead to favorable storage or curtailment energetics, resultant $EROI_{grid}$ when storage is employed, and requisite cycle life for batteries to yield better net energetics over curtailment. By definition $EROI_{grid}$ is the inverse of ε_g. Using equation 6 we arrive at $EROI_{grid}$:

$$EROI_{grid} = \frac{1-\phi+\eta\phi}{\varepsilon_r + \phi\eta\varepsilon_s}. \tag{7}$$

and similarly, $\varepsilon_r = \frac{1}{EROI}$ and $\varepsilon_s = \frac{1}{ESOI_e}$, so in terms of $EROI$ and $ESOI_e$,

$$EROI_{grid} = \frac{1-\phi+\eta\phi}{\frac{1}{EROI} + \frac{\eta\phi}{ESOI_e}}. \tag{8}$$

Symbol	Units	Name	Notes
		Energy intensities	
ε_r	$\left[\frac{kWh_e}{kWh_e}\right]$	renewable technology intensity	embodied electrical energy per unit electricity generated
ε_s	$\left[\frac{kWh_e}{kWh_e}\right]$	storage technology intensity	cradle-to-gate embodied electrical energy per unit electrical energy from storage $\varepsilon_s = \frac{\epsilon_e}{\lambda\eta D} = \frac{1}{ESOI_e}$
ε_c	$\left[\frac{kWh_e}{kWh_e}\right]$	curtailed renewable technology intensity	$\varepsilon_c = \frac{\varepsilon_r}{(1-\phi)}$
ε_g	$\left[\frac{kWh_e}{kWh_e}\right]$	power grid intensity	$\varepsilon_g = \frac{\varepsilon_r+\eta\varepsilon_s\phi}{1-\phi+\phi\eta}$
		Energy Returned on Investment Ratios	
$EROI$	$\left[\frac{kWh_e}{kWh_e}\right]$	renewable technology EROI	electrical energy generated per unit of embodied electrical energy $EROI = \frac{1}{\varepsilon_r}$
$ESOI_e$	$\left[\frac{kWh_e}{kWh_e}\right]$	energy stored on energy investment	electrical energy delivered from storage per unit of embodied electrical energy $ESOI_e = \frac{\lambda\eta D}{\epsilon_e}$
$EROI_{curt}$	$\left[\frac{kWh_e}{kWh_e}\right]$	curtailed renewable technology EROI	electrical energy generated less curtailment per unit embodied electrical energy $EROI_{curt} = (1-\phi)EROI$
$EROI_{grid}$	$\left[\frac{kWh_e}{kWh_e}\right]$	power grid EROI	electrical energy generated and stored per unit embodied electrical energy $EROI_{grid} = \frac{1-\phi+\eta\phi}{\frac{1}{EROI}+\frac{\eta\phi}{ESOI_e}}$
		Variables	
ϵ_e	$\left[\frac{kWh_e}{kWh_e}\right]$	storage cradle-to-gate embodied energy	cradle-to-gate embodied electrical energy per unit of electrical energy storage capacity
λ	[#]	cycle life	total number of charge-discharge cycles at a specific depth-of-discharge
D	[—]	depth-of-discharge	the fraction of a storage technologies capacity that undergoes charge and discharge each cycle
η	[—]	storage technology's AC-AC efficiency	storing and delivering electrical energy from and to the power grid

Table 1 A table listing terms and variables used in calculations.

2.1 EROI break-even between storage and curtailment

A simple power grid consisting of renewable generation and energy storage has an energy intensity of ε_g (equation 6). Assuming if fraction ϕ of a generation resource's energy is not stored, it is curtailed, curtailment of a resource reduces its energy intensity to

$$\varepsilon_c = \frac{\varepsilon_r}{(1-\phi)}. \tag{9}$$

By setting $\varepsilon_c = \varepsilon_g$ we establish a decision metric that determines when, form a net energy perspective, a resource should be stored or not stored as a function of the variables involved: ε_r, ε_s, and ϕ. Is it better to curtail or store? Is it better to invest ε_r and get back $(1-\phi)$, or is it better to invest $(\varepsilon_r + \eta\phi\varepsilon_s)$ and get back $(1-\phi+\eta\phi)$? Expanding ε_c and ε_g using equations 9 and 6,

$$\frac{\varepsilon_r}{(1-\phi)} = \frac{\varepsilon_r + \phi\eta\varepsilon_s}{1-\phi+\eta\phi}. \tag{10}$$

Multiplying through by $(1-\phi)(1-\phi+\phi\eta)$,

$$\varepsilon_r - \phi\varepsilon_r + \phi\eta\varepsilon_r = \varepsilon_r + \phi\eta\varepsilon_s - \phi\varepsilon_r - \phi^2\eta\varepsilon_s. \tag{11}$$

Cancelling terms from both sides,

$$\phi\eta\varepsilon_r = \phi\eta\varepsilon_s - \phi^2\eta\varepsilon_s. \tag{12}$$

Finally, dividing through by ϕ and rearranging,

$$\frac{\varepsilon_r}{\varepsilon_s} = 1-\phi, \tag{13}$$

and in terms of EROI and ESOI$_e$ as shown in the main text,

$$\frac{ESOI_e}{EROI} = 1-\phi \tag{14}$$

When this equality holds, curtailment and storage yield the same grid scale EROI. Otherwise, from an energy efficiency perspective, one of two conditions exists:

$$\frac{ESOI_e}{EROI} \Rightarrow \begin{cases} \text{store if } > 1-\phi \\ \text{curtail if } < 1-\phi. \end{cases} \tag{15}$$

This inequality can be rearranged to probe individual variables. For example, to determine what minimum ESOI$_e$ is required to achieve a net energy gain over curtailment then following arrangement is employed,

$$ESOI_e > \frac{1-\phi}{EROI} \tag{16}$$

Individual variables can be expanded to further probe the effects that technological attributes have on the decision to store or curtail. In figure 5 of the main text we determine the minimum cycle required by electrochemical storage technologies. Expanding ESOI$_e$ and rearranging equation 16, the minimum cycle life requirement is

$$\lambda > \frac{\epsilon_e(1-\phi)}{(\eta D)EROI}. \tag{17}$$

3 Present day rates of curtailment

Table 2 lists the amount of energy curtailed and the percentage of potential wind power curtailed for several power generation regions. Curtailment rates are expected to increase as wind and solar comprise a larger fraction of the generation mix[3,4].

region	2007	2008	2009	2010	2011	2012
Electric Reliability Council of Texas (ERCOT)	109 GWh (1.2%)	1,417 (8.4%)	3,872 (17.1%)	2,067 (7.7%)	2,622 (8.5%)	1,038 (3.7%)
Southwestern Public Service Company (SPS)	n/a	0 (0.0%)	0 (0.0%)	0.9 (0.0%)	0.5 (0.0%)	n/a
Public Service Compancy of Colorado (PSCo)	n/a	2.5 (0.1%)	19.0 (0.6%)	81.5 (2.2%)	63.9 (1.4%)	n/a
Northern States Power Company (NSP)	n/a	25.4 (0.8%)	42.4 (1.2%)	42.6 (1.2%)	54.4 (1.2%) (3.1%)	120.5
Midwest Independent System Operator (MISO), less NSP	n/a	n/a	250 (2.2%)	781 (4.4%)	657 (3.0%)	726 (2.5%)
Bonneville Power Administration (BPA)	n/a	n/a	n/a	4.6 (0.1%)	128.7 (1.4%)	70.8 (0.7%)
PJM	n/a	n/a	n/a	n/a	n/a	111.6 (1.8%)
Total Across These Seven Areas:	109 (1.2%)	1,445 (5.6%)	4,183 (9.6%)	2,978 (4.8%)	3,526 (4.8%)	2,067 (2.7%)

Source: Wiser et al., 2012 Wind Technologies Market Report, table 5

Table 2 A table listing energy curtailed in GWh and in percentage of potential wind generation in various electric power control regions.

4 Data: EROI and ESOI$_e$

We use net energy ratios to quantitatively compare the ability of energy processes and services to return useful energy to society. One such ratio EROI (Energy Returned on Invested) is a general net energy ratio that allows comparisons between different technologies [Hall, Cleveland and Kaufmann, 1986]. Different forms of energy–heat, gravitational potential, kinetic, chemical, electrical, etc–vary in their efficiency in conversion to mechanical work. In this study we recast all EROI values in terms of electricity. Electricity is the form most efficiently converted into other forms with the least amount of 2$^{\text{nd}}$ law losses.

4.1 Renewable EROI Data

We acquired energy intensity values and EROI values from several studies in the literature. Discussion of the meta-analysis method used to collate the data are discussed in[5,6]. Sources for the estimates are presented in Table 3. Figure 3 show ESOIe values for storage technologies. Thin film solar technologies have greater EROI values than wafer technologies (sc-Si and mc-Si). Reported EROI values for wind farms vary from less than 5 to greater than 100. On average the EROI for on shore wind is 86 for the studies included in our analysis. Reported values for solar EROI depend on the technology. We have grouped technologies into two categories: wafer and thin film.

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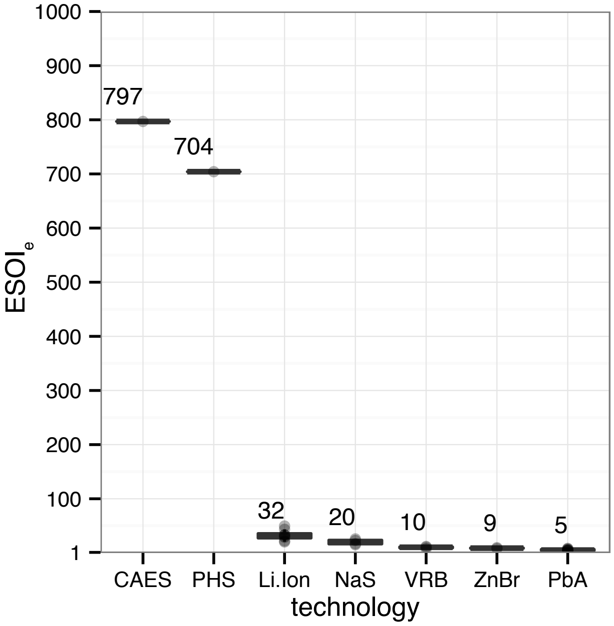

Figure 2 Electrical energy stored on invested (ESOI$_e$) values for storage technologies obtained from peer-reviewed sources are plotted by circles. Limited storage LCA data leads to box and whisker statistics that cluster near median values as indicated by text labels.

Table 3 Studies found from search and screening process

Reference	Year	Technology	Location	Analysis type
[7]	1995	PV	India	Process
[8]	1997	PV	Japan	Process
[9]	1997	PV	US	Process
[10]	2000	PV	Unspecified	Process
[11]	2001	PV	Europe	Process
[12]	2001	PV	US	Process
[13]	2002	PV	India	Process
[14]	2002	PV	Europe	Process
[15]	2004	PV	Europe	Process
[16]	2004	PV	India	Process
[17]	2004	PV	Europe	Process
[18]	2005	PV	Europe	Process
[19]	2006	PV	US	Process
[20]	2006	PV	Europe	Process
[21]	2006	PV	US	Process
[22]	2006	PV	Singapore	Process
[23]	2007	PV	Europe	Process
[24]	2007	PV	US	Process
[25]	2007	PV	Europe	Process
[26]	2008	PV	China	Process
[27]	2008	PV	Many	Process
[28]	2009	PV	Europe	Process
[29]	2009	PV	US	Process
[30]	2009	PV	Europe	Process
[31]	2010	PV	US/Canada	Process
[32]	2010	PV	US	Hybrid
[33]	2010	PV	China/Japan	Process
[34]	2011	PV	Europe	Process
[35]	2011	PV	Europe	Process
[2]	2002	Wind	Many	Meta-analysis
[36]	2004	Wind	Europe	Process
[37]	2005	Wind	Canada	Process
[38]	2006	Wind	Europe	Process
[39]	2006	Wind	Europe	Process
[40]	2008	Wind	Taiwan	Process
[41]	2008	Wind	Europe	Process
[42]	2009	Wind	Europe	Process
[43]	2009	Wind	Europe	Process
[44]	2009	Wind	Europe	Process
[45]	2009	Wind	Australia	Hybrid
[46]	2010	Wind	Many	Meta-analysis
[47]	2011	Wind	Europe	Process
[47]	2011	Wind	Europe	Process
[48]	2011	Wind	Europe	Process
[49]	2011	Wind	Europe	Process
[50]	2011	Wind	China	Process
[51]	2011	Wind	China	Process
[52]	2011	Wind	Europe	Process
[53]	2012	Wind	Europe	Process
[54]	2012	Wind	Canada	Process

4.2 ESOI$_e$ data

Embodied electrical energy per unit capacity, ϵ_e data for $ESOI_e$ calculations were obtained from several sources[55–57]. As discussed in Sullivan and Gaines, 2010[57], and taken verbatim from Barnhart and Benson, 2013[58],

> We compare the energy costs of storage technologies by considering their cradle-to-gate embodied energy requirements. In a cradle-to-gate analysis, a specific Life Cycle Assessment (LCA) valuation, a technology's use phase and disposal phase are omitted. We obtained these values for storage technologies from published LCA studies[55–57]. A recent review of battery LCA by Argonne National Laboratory recognizes that battery LCA data often lack detailed energy and material flows in the best of cases[57]. More commonly data is non-existent or decades out-of-date. We can, using these data, consider the implications of energy costs, obtain comparisons between technologies, and identify technology attributes that, if targeted by research, will lead to reductions in energy use in storage deployment. We converted values from study specific units to an embodied energy storage ratio, ϵ_{gate}–a dimensionless number that indicates the amount of embodied energy required for one energy unit of storage capacity.
>
> We obtained LCA data for technologies from three sources[55–57]. Additional LCA data for materials were obtained from various reports and software databases[59–64]. We truncate values to cradle-to-gate from studies that included cradle-to-grave analyses for consistency *e.g.* Denholm and Kulcinski, 2004[55]. Values reported by Rydh and Sanden, 2005[56] where in units of MJ primary fuel per kg of battery. These were converted form per kg to per MJ capacity by assuming a practical energy density for electrochemical storage technologies (see Table 4).

Table 4 Electrochemical storage technology properties

technology	reactants	m_f	$\rho_{theoretical}$ ($\rho_{practical}$)
Li-Ion	Li_xC_6	Li 0.04	448 Wh/kg
(cylindrical spiral-bound)	$Li_{1-x}CoO_2$	Co 0.35	(200)
NaS	$2Na + xS$	Na 0.42	792
(NGK-Tepco)	$(x = 5 - 3)$	S 0.58	(170)
PbA	$Pb + PbO_2$	Pb 0.93	252
(prismatic)	H_2SO_4		(35)
VRB	$V(SO_4)$	V 0.31	167^a
	$VO_2(HSO_4)$		(30^a)
ZnBr	$Zn + Br_2$	Zn 0.29	436
		Br 0.71	(70)

Sources: All information from[65] unless otherwise noted, [a] [66]

As discussed in the main text, we adjusted components of energy ratios cast in terms of primary energy by applying a reasonable conversion factor. Specifically, embodied energy per unit storage capacity data, ϵ, from[58] were multiplied by 0.3 to make an energy quality conversion from primary energy to electrical energy. ϵ_e values in this study differ from ϵ_{gate} values used in[58], because they are cast in terms of embodied electrical energy, not embodied primary energy. We justify casting ESOI$_e$ in terms of electrical energy because curtailed energy is electrical, not primary energy. Figure 3 is a whisker plot of calculated ESOI$_e$ data for technologies considered in this analysis. The lack of storage LCA data leads to whisker plots that collapse on median values.

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References

1. Hall, C.A.S.; Cleveland, C.J.; Kaufmann, R.K. *Energy and resource quality: the ecology of the economic process*; University Press of Colorado, 1992.
2. Lenzen, M.; Munksgaard, J. Energy and CO2 life-cycle analyses of wind turbines–review and applications. *Renewable Energy* **2002**, *26*, 339–362.
3. Denholm, P.; Margolis, R.M. Evaluating the limits of solar photovoltaics (PV) in traditional electric power systems. *Energy Policy* **2007**, *35*, 2852–2861.
4. Wiser, R.; Bolinger, M. 2011 Wind Technologies Market Report. Technical Report August, U.S. Department of Energy, 2012.
5. Dale, M.; Benson, S.M. Energy balance of the global photovoltaic (PV) industry - Is the PV industry a net electricity producer ? *Environmental Science & Technology* **2013**, p. dx.doi.org/10.1021/es3038824.
6. Dale, M.; Benson, S.M. A Comparative Analysis of Energy Costs of Photovoltaic, Solar Thermal, and Wind Electricity Generation Technologies. *Applied Science* **2013**, *3*, 325–337.
7. Prakash, R.; Bansal, N.K. Energy Analysis of Solar Photovoltaic Module Production in India. *Energy Sources* **1995**, *17*, 605–613.
8. Kato, K.; Murata, A.; Sakuta, K. An evaluation on the life cycle of photovoltaic energy system considering production energy of off-grade silicon. *Solar Energy Materials and Solar Cells* **1997**, *47*, 95–100.
9. Keoleian, G.A.; Lewis, G.M. Application of life-cycle energy analysis to photovoltaic module design. *Progress in Photovoltaics: Research and Applications* **1997**, *5*, 287–300.
10. Alsema, E.A. Energy pay-back time and CO2 emissions of PV systems. *Progress in Photovoltaics: Research and Applications* **2000**, *8*, 17–25.
11. Frankl, P. Life Cycle Assessment of Renewables: Present Issues, Future Outlook and Implications for the Calculation of External Costs, 2001.
12. Knapp, K.; Jester, T. Empirical investigation of the energy payback time for photovoltaic modules. *Solar Energy* **2001**, *71*, 165–172.
13. Mathur, J.; Bansal, N.K.; Wagner, H.J. Energy and Environmental Correlation for Renewable Energy Systems in India. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* **2002**, *24*, 19–26.
14. GEMIS. Global Emissions Model for Integrated Systems, 2002.
15. Gürzenich, D.; Wagner, H.J. Cumulative energy demand and cumulative emissions of photovoltaics production in Europe. *Energy* **2004**, *29*, 2297–2303.
16. Mathur, J.; Bansal, N.K.; Wagner, H.J. Dynamic energy analysis to assess maximum growth rates in developing power generation capacity: case study of India. *Energy Policy* **2004**, *32*, 281–287.
17. Krauter, S.; Ruther, R. Considerations for the calculation of greenhouse gas reduction by photovoltaic solar energy. *Renewable Energy* **2004**, *29*, 345–355.
18. Battisti, R.; Corrado, A. Evaluation of technical improvements of photovoltaic systems through life cycle assessment methodology. *Energy* **2005**, *30*, 952–967.
19. Fthenakis, V.; Alsema, E. Photovoltaics energy payback times, greenhouse gas emissions and external costs: 2004 - early 2005 status. *Progress in Photovoltaics* **2006**, *14*, 275–280.
20. Muneer, T.; Younes, S.; Lambert, N.; Kubie, J. Life cycle assessment of a medium-sized photovoltaic facility at a high latitude location. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy* **2006**, *220*, 517–524.
21. Mason, J.E.; Fthenakis, V.M.; Hansen, T.; Kim, H.C. Energy payback and life-cycle CO2 emissions of the BOS in an optimized 35 MW PV installation. *Progress in Photovoltaics: Research and Applications* **2006**, *14*, 179–190.
22. Kannan, R.; Leong, K.C.; Osman, R.; Ho, H.K.; Tso, C.P. Life cycle assessment study of solar PV systems: An example of a 2.7 kW(p) distributed solar PV system in Singapore. *Solar Energy* **2006**, *80*, 555–563.
23. Mohr, N.J.; Schermer, J.J.; Huijbregts, M.A.J.; Meijer, A.; Reijnders, L. Life cycle assessment of thin-film GaAs and GaInP/GaAs solar modules. *Progress in Photovoltaics Research and Applications* **2007**, *15*, 163–179.
24. Pacca, S.; Sivaraman, D.; Keoleian, G.A. Parameters affecting the life cycle performance of PV technologies and systems. *Energy Policy* **2007**, *35*, 3316–3326.

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25. Raugei, M.; Bargigli, S.; Ulgiati, S. Life cycle assessment and energy pay-back time of advanced photovoltaic modules: CdTe and CIS compared to poly-Si. *Energy* **2007**, *32*, 1310–1318.

26. Ito, M.; Kato, K.; Komoto, K.; Kichimi, T.; Kurokawa, K. A comparative study on cost and life-cycle analysis for 100 MW very large-scale PV (VLS-PV) systems in deserts using m-Si, a-Si, CdTe, and CIS modules. *Progress in Photovoltaics: Research and Applications* **2008**, *16*, 17–30.

27. Stoppato, A. Life cycle assessment of photovoltaic electricity generation. *Energy* **2008**, *33*, 224–232.

28. Roes, A.L.; Alsema, E.A.; Blok, K.; Patel, M.K. Ex-ante environmental and economic evaluation of polymer photovoltaics. *Progress in Photovoltaics: Research and Applications* **2009**, *17*, 372–393.

29. Fthenakis, V.; Kim, H.C.; Held, M.; Raugei, M.; Krones, J. Update of PV energy payback times and life-cycle greenhouse gas emissions. Book of Proceedings of the 24th European Photovoltaic Solar Energy Conference, 2009, pp. 21–25.

30. Raugei, M.; Frankl, P. Life cycle impacts and costs of photovoltaic systems: Current state of the art and future outlooks. *Energy* **2009**, *34*, 392–399.

31. Amor, M.B.; Lesage, P.; Pineau, P.O.; Samson, R. Can distributed generation offer substantial benefits in a Northeastern American context? A case study of small-scale renewable technologies using a life cycle methodology. *Renewable and Sustainable Energy Reviews* **2010**, *14*, 2885–2895.

32. Zhai, P.; Williams, E.D. Dynamic Hybrid Life Cycle Assessment of Energy and Carbon of Multicrystalline Silicon Photovoltaic Systems. *Environmental Science & Technology* **2010**, *44*, 7950–7955.

33. Nishimura, A.; Hayashi, Y.; Tanaka, K.; Hirota, M.; Kato, S.; Ito, M.; Araki, K.; Hu, E.J. Life cycle assessment and evaluation of energy payback time on high-concentration photovoltaic power generation system. *Applied energy* **2010**, *87*, 2797–2807.

34. Laleman, R.; Albrecht, J.; Dewulf, J. Life Cycle Analysis to estimate the environmental impact of residential photovoltaic systems in regions with a low solar irradiation. *Renewable and Sustainable Energy Reviews* **2011**, *15*, 267–281.

35. Held, M.; Ilg, R. Update of environmental indicators and energy payback time of CdTe PV systems in Europe. *Progress in Photovoltaics Research and Applications* **2011**, *19*, 614–626.

36. Elsam. Life cycle assessment of offshore and onshore sited wind farms, 2004.

37. Khan, F.I.; Hawboldt, K.; Iqbal, M.T. Life Cycle Analysis of wind-fuel cell integrated system. *Renewable Energy* **2005**, *30*, 157–177.

38. Vestas. Life cycle assessment of electricity produced from onshore sited wind power plants based on Vestas V82-1.65MW turbines, 2006.

39. Vestas. Life cycle assessment of offshore and onshore sited wind power plants based on Vestas V90-3.0 MW turbines, 2006.

40. Lee, Y.M.; Tzeng, Y.E. Development and Life-Cycle Inventory Analysis of Wind Energy in Taiwan. *Journal of Energy Engineering* **2008**, *134*, 53–57.

41. Ardente, F.; Beccali, M.; Cellura, M.; Brano, V.L. Energy performances and life cycle assessment of an Italian wind farm. *Renewable and Sustainable Energy Reviews* **2008**, *12*, 200–217.

42. Martínez, E.; Sanz, F.; Pellegrini, S.; Jiménez, E.; Blanco, J. Life-cycle assessment of a 2-MW rated power wind turbine: CML method. *The International Journal of Life Cycle Assessment* **2009**, *14*, 52–63.

43. Weinzettel, J.; Reenaas, M.; Solli, C.; Hertwich, E.G. Life cycle assessment of a floating offshore wind turbine. *Renewable Energy* **2009**, *34*, 742–747.

44. Tremeac, B.; Meunier, F. Life cycle analysis of 4.5MW and 250W wind turbines. *Renewable and Sustainable Energy Reviews* **2009**, *13*, 2104–2110.

45. Crawford, R.H. Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield. *Renewable and Sustainable Energy Reviews* **2009**, *13*, 2653–2660.

46. Kubiszewski, I.; Cleveland, C.J.; Endres, P.K. Meta-analysis of net energy return for wind power systems. *Renewable energy* **2010**, *35*, 218–225.

47. Vestas. Life cycle assessment of electricity production from a V80-2.0 MW Gridstreamer wind plant, 2011.

48. Vestas. Life cycle assessment of electricity production from a Vestas V112 turbine wind plant, 2011.

49. Vestas. Life cycle assessment of electricity production from a V100-1.8 MW Gridstreamer wind plant, 2011.

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50. Chen, G.Q.; Yang, Q.; Zhao, Y.H. Renewability of wind power in China: A case study of nonrenewable energy cost and greenhouse gas emission by a plant in Guangxi. *Renewable and Sustainable Energy Reviews* **2011**, *15*, 2322–2329.

51. Yang, Q.; Chen, G.Q.; Zhao, Y.H.; Chen, B.; Li, Z.; Zhang, B.; Chen, Z.M.; Chen, H. Energy cost and greenhouse gas emissions of a Chinese wind farm. *Procedia Environmental Sciences* **2011**, *5*, 25–28.

52. Wagner, H.J.; Baack, C.; Eickelkamp, T.; Epe, A.; Lohmann, J.; Troy, S. Life cycle assessment of the offshore wind farm alpha ventus. *Energy* **2011**, *36*, 2459–2464.

53. Guezuraga, B.; Zauner, R.; Pölz, W. Life cycle assessment of two different 2 MW class wind turbines. *Renewable Energy* **2012**, *37*, 37–44.

54. Kabir, M.R.; Rooke, B.; Dassanayake, G.D.; Fleck, B.A. Comparative life cycle energy, emission, and economic analysis of 100 kW nameplate wind power generation. *Renewable Energy* **2012**, *37*, 133–141.

55. Denholm, P.; Kulcinski. Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems. *Energy Conversion and Management* **2004**, *45*, 2153–2172.

56. Rydh, C.; Sandén, B. Energy analysis of batteries in photovoltaic systems. Part I: Performance and energy requirements. *Energy Conversion and Management* **2005**, *46*, 1957–1979.

57. Sullivan, J.L.; Gaines, L. A Review of Battery Life-Cycle Analysis : State of Knowledge and Critical Needs ANL/ESD/10-7. Technical report, Argonne National Laboratory, Oak Ridge, TN, 2010.

58. Barnhart, C.J.; Benson, S. On the importance of reducing the energetic and material demands of electrical energy storage. *Energy Environ. Sci.* **2013**, pp. –.

59. Hammond, P.G.; Jones, C. Embodied energy and carbon in construction materials. *Proc. Instn Civil. Engrs: Energy* **2008**, *161*, 4434–4443.

60. ESU-services. Abstract of LCIs, 2010.

61. (USGS). Mineral Commodity Summaries. Technical report, U.S. Geological Survey, Reston, Virginia, 2011.

62. Gabi. PE International (ed.) Gabi Software, Gabi 5, 2012.

63. Struck, R.T.; Kulik, M.D.; Gorin, E. Removal of Sulfur Dioxide from Power Plant Stacks by a Modified Claus Process. *Consolidation Coal Company* **1969**.

64. Merier, P.; Kulcinski, G. Life-Cycle Energy Cost and Greenhouse Gas Emissions for Gas Turbine Power. Technical Report December, Fusion Technology Institute, University of Wisconsin-Madison, Madison, WI, 2000.

65. Reddy, T.; Linden, D. *Linden's Handbook of Batteries*, 4th editio ed.; McGraw-Hill Prof Med/Tech, 2010; p. 1200.

66. Scott, I.; Lee, S.H. Battery Energy Storage. In *Large Energy Storage Systems Handbook*; Barnes, F.S.; Levine, J.G., Eds.; CRC Press: Boca Raton, FL, 2011; chapter 6, pp. 153–181.