Indicators To Determine Winning Renewable Energy Technologies with an Application to Photovoltaics

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Several forms of renewable energy compete for supremacy or for an appropriate role in global energy supply. A form of renewable energy can only play an important role in global energy supply if it fulfills several basic requirements. Its capacity must allow supplying a considerable fraction of present and future energy demand, all materials for its production must be readily available, land demand must not be prohibitive, and prices must reach grid parity in the nearer future. Moreover, a renewable energy technology can only be acceptable if it is politically safe. We supply a collection of indicators which allow assessing competing forms of renewable energy and elucidate why surprise is still a major factor in this field, calling for adaptive management. Photovoltaics (PV) are used as an example of a renewable energy source that looks highly promising, possibly supplemented by solar thermal electricity production (ST). We also show why energy use will contribute to land use problems and discuss ways in which the right choice of renewables may be indispensible in solving these problems.

Basic Criteria for Any Renewable Energy

Over the past few years, renewable energy production has grown rapidly from investments of approximately $40 billion globally in 2005 to $120 billion in 2008 (*1*). Different renewable energy sources differ in their potential to sustain ongoing capacity expansion and to supply energy or heating when and where it is needed at acceptable costs. These differences in potential should be investigated before large investments are made that may ultimately fail.

A core question is whether the energy path that is being implemented will be able to meet the demands of a global population which might surpass 10 billion in 2060, and a global economy which might grow by a factor of 18 in this century, based on the annual economic growth of 3.3% during 1970−2000 (*2*). If energy efficiency is assumed to grow with 1.6%y^{-1}, as was observed globally during 1990−2006 (*3*), primary energy demand would grow approximately 5-fold by 2100.

Steady capacity expansion by individual renewable energy technologies can only be sustained if the required resources are available and land demands are considered to be feasible (e.g., equal to at most a few percent of a country's total land area). Growth rates will depend on when grid parity is reached, on investors' expectations regarding grid parity, and on policies to ensure that the technology gets appropriate grid access.

The four indicators proposed here are measures of the performance of specific renewable energy technologies relative to these central criteria:

1. Is the potential of energy supplied by a renewable energy source sufficient to meet at least a considerable proportion of global energy needs?
2. Are necessary materials available or are there intrinsic bottlenecks which can only be overcome with difficulties, if at all?
3. Will the renewable energy technology reach grid parity - and when?
4. Is the required land area acceptable, and are there significant impacts on water supply or quality?

The questions motivating the first, third, and fourth of our indicators have been discussed previously in evaluations of the technical, geographic, and economic potential of renewable energy sources (*4*−*7*). These three types of potential provide a comprehensive set of criteria for renewable energy potential (*4*−*6*, *8*). We propose a quantitative format to apply these criteria to the potential of renewable energy sources in the form of indicators. The technical potential, which is quantified in our first indicator, is the theoretical limit of energy that can be produced from a given renewable after accounting for conversion losses. The economic and geographic potential describe, respectively, restrictions resulting from cost competitiveness and land requirements. These terms are quantified in our third and fourth indicator.

A central conclusion of previous studies is that the technical potential of technologies other than solar is insufficient, in particular given anticipated future demand (*4*, *5*, *9*, *10*). Solar energy has the by far highest potential of all renewables (*5*, *9*). Whether solar energy will indeed be able to play a dominant role in future energy production will depend on its performance with regard to the other three indicators - resource availability, production costs, and land demand. Recent new results and the considerable technological advances in PV technologies now enable a much greater level of detail for such an analysis.

These indicators can also help identify promising technologies that energy policies should focus on and necessary supportive conditions for sustained growth of renewable energy markets (*10*−*12*). Due to the long lifetime of investments in the energy sector, decisions on energy supply, demand, and efficiency will be of decisive importance throughout this century. Power plants can have lifetimes of 60 years. Buildings have lifetimes of 100 years or more, consume about 20−30% of primary energy, and are responsible for at least a third of global CO_2 emissions (*13*). Zero- or net-zero energy buildings have recently become state-of-the-art. They can, additionally, rely on solar and wind energy (*13*, *14*).

Indicators are important tools in adaptive management, i.e. iterative decision making approaches that are updated with increased understanding of the involved uncertainties.

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TABLE 1. Estimated Technical Potential of Different Forms of Renewable Energy in TW Adjusted to the Same Underlying Assumptions Where Possible

renewable energy	potential	remarks
ocean (tides and waves)	0.9–4.6 (*61*)	This is an upper boundary - according to Lewis (*61*) only 0.9 TW are feasible to exploit.
wind (onshore only)	11(*4*)	theoretical potential (total global energy content of wind), potential also overestimated due to assumption of 100% conversion efficiency
	2–4 (*61*)	theoretical potential (total global energy content of wind)
wind	96 (*62*)	total global energy content from land and 200 m offshore, conversion efficiency as given by General Electric in 2008/2009
	72 (*63*)	over land at 80 m
biomass	20 (*61*)	31% of the total global land area
	34.4 (*4*)	31% of global land area, heating value of 19 GJ
geothermal	11 (*61*)	an unrealistic 100% efficiency is assumed
	1.5–60 (*64*)	includes heating
microalgae	45(*43*)	2% of global land area, 10% photosynthetic efficiency
solar	438 (*4*)	12% efficiency, ca. 14% of total global land area (21,000,000 km^2)[a]
	424–574 (*61*)	upper limit for high insolation conditions, lower limit for an area mix including significant proportion of less suitable areas (*61*)
	504[a]	
	517(*40*)	12% efficiency, area with high solar radiation: 7.8% of global land area (11,500,000 km^2)

[a] Our calculation, Supporting Information.

This is necessary for renewable energy policy given the history of rapid and often not well predicted developments. Examples are the recent withdrawal of support for fuel cells by most companies due to a shift of interest toward electric vehicles (EVs) and the debate surrounding biofuels, given potential impacts on food supply, high costs, and lower than expected emissions reduction (*15, 16*).

With the rapid pace of current technological and political developments, more surprises are certain. Indicators facilitate comparing current developments with earlier predictions and help to become aware of surprises at an early stage.

Does the Potential of a Particular Renewable Energy Source Suffice for Global Energy Supply?

Table 1 lists estimates of the potential of the main renewable energy sources. Differences in estimates and updates with new research affect the value of the indicators but should not affect their form. Our estimate of the potential of solar energy assumes the U.S. average solar insolation of 200 Wm^{-2} y^{-1} and PV efficiency of 12%, which is likely a conservative assumption (Supporting Information).

Geothermal sources are only renewable if heat extraction does not exceed the amount that can be replenished by the reservoir (*17*). The estimated potential for wind and bioenergy may become higher with new research but will remain limited due to the origin of both from the energy of the sun (*6*). Thus the potential of solar energy is orders of magnitude larger than that of wind and biomass (*6*). Agricultural plants capture less than 0.5% of the energy that can be generated with PV in comparable locations. Efficient microalgae in tropical locations produce about 15% of PV production (Supporting Information).

Table 1 shows that ocean tide and wave power, wind and geothermal together could produce between 4.4–75.6 terawatt (TW). 4.4 TW is much less than the global energy demand of 15.8 TW in 2007 (*18*). 75.6 TW is sufficient for current demand but will probably not meet increasing future demand. At above 420 TW, the potential of solar energy is significantly larger than that of all other forms of renewable energy combined. It could meet a 20-fold increase in demand.

The competitive value of a renewable r_i further depends on how soon it will be able to meet a significant proportion of demand. The coverage $C_{i,j}(t)$ of demand $D_j(t)$ in region j by r_i at time t is

$$C_{i,j}(t) = P(r_{i,j}) / D(t)_j \qquad (1)$$

where $P(r_{i,j})$ is the energy generated by r_i. With exponential growth of demand, (1) takes the form

$$C_{i,j}(t) = P(r_{i,j}) / D_{j,0}e^{a_j t} \qquad (2)$$

where a_j is the growth rate of demand $D(t)_j$ in j, and $D_{j,0}$ is demand at time $t = 0$.

The time in years that technology r_i would take to fulfill *present* energy demand is

$$T_i = (D_j - I_j) / M_i \qquad (3)$$

Here, I_j is the present installed capacity of r_i, and M_i is the annual production of additional capacity. The present annual global PV production capacity is 10 GW, and about 10 GW have been installed. At this rate, 1500 years will be needed to meet present global demand. For comparison, in 2008, hydropower capacity reached 945 GW, wind power 121 GW, biomass 52 GW, and geothermal power 10 GW (*1*).

Incorporating the present growth rate $b_{i,j}$ of renewable r_i gives the next indicator, the time t_i r_i will need to meet present energy demand

$$T_{i,b} = (D_j - I_{i,j}) / (M_i \exp(t_i \ln(1 + b_{i,j})) \text{ or } t_i = \ln((D_j - I_{i,j}) / M_i) / \ln(1 + b_{i,j}) \qquad (4)$$

Here, $I_{i,j}$ and M_i are as above, and D_j is the (fixed) total energy demand of region j.

We will illustrate this indicator for the future growth of PV. Several groups have developed scenarios of the future growth of the global PV market (Table S1). The more conservative scenarios have already fallen behind installed capacity, with the 2008 capacity surpassing the capacity projected for 2010 by a factor of 1.5–2.5 (Table S1). The average annual growth during 2010–2020 among the remaining scenarios is 21%. This compares to a growth rate of 50% over the last 5 years (*19*). If annual growth leveled off to an average of $b_{i,j} = 20\%$, t_i would decrease to 43.9 years;

TABLE 2. Layer Thickness of CdTe Cells, Amount of Te Needed per TW, Cumulative Amount of Te Available, Resulting Annual Production of CdTe PV, and Maximum PV Installed in 2008 and by 2020, 2050, and 2065 according to Zweibel (*20*),[a] Fthenakis (*21*),[b] and Our Calculations (See the Supporting Information)[c,d]

	layer (μm)	t/TW	cum. Te (t)	GW PV/year	max TW installed
2008	3.3[b]	880,000[b]			
2020	1−2.5[b]	150,000−400,000[b]	8824[c]	14−38[b]	0.02−0.04[b]
2050	0.5−1[c]	75,000−150,000[c]	51,184−90,004[c]	19−149[b]	0.1−0.5[b]
					1.1−4.4[c]
2065	0.5[a]	55,000[a]	330,000[a]	20−211[b]	6[a]
			66,184−144,534[c]		0.3−2.6[b]
					1.6−8.5[c]

[a] Zweibel, ref *20*. [b] Fthenakis, ref *21*. [c] Our calculations (see the Supporting Information). [d] To convert GWp and TWp in GW and TW, 1 Wp is assumed to translate into 0.2 W capacity (*20*).

TABLE 3. Cumulative Amount of CIGS Materials Indium (In) and Selenium (Se), Thin-Film Silicon Material Germanium (Ge), Amount of Te Needed per TW, and Maximum PV Installed by 2020, 2050, 2065, and 2075 According to Zweibel (*20*),[a] Fthenakis (*21*),[b] and Our Calculations (See the Supporting Information)[c]

	cum. 2065 (t)	t/TW 2020	t/TW 2065	max. TW 2020	max. TW 2050	max. TW 2065	max. TW 2075
In	10.000[a]	11,000−20,000[b]	28,000[a]	0.004−0.01[c]	0.5−2[c]	3.4[b]	1−5.3[c]
Se	2,900,000[a]	N/A	45,000[a]	N/A	N/A	60[b]	N/A
Ge	N/A	36,000−48,000[b]	N/A	0.03−0.09[c]	0.2−1[c]	N/A	0.3−3.1[c]

[a] Zweibel, ref *20*. [b] Fthenakis, ref *21*. [c] Our calculations (see the Supporting Information).

with continued growth at 50% t_i would decrease to 19.7 years. First Solar, the main producer of CdTe (cadmium telluride) cells, has grown by 100% during each of the last 3 years and now has an annual production capacity exceeding 1 GW. At this growth rate it could produce 15 TW annually within 13.9 years.

We conclude that PV can only become a major player at long-term excessive growth rates. A second major conclusion is that the potential of solar energy is large enough to meet current energy needs and plausible future demand through this century. This motivates us to investigate our remaining indicators mainly for solar energy.

Are the Resources Available for Large Scale Production of a Specific Renewable Energy?

Resource availability should be investigated and monitored for all new renewable energy candidates. If such an investigation had been carried out before initiating large-scale promotion of biofuel, subsidies might not have become available. Bottlenecks in material supply can also significantly slow down market expansion (*11*).

We begin by evaluating material availability for large-scale second generation PV production. Second generation or thin-film PV consist of a substrate with one or several very thin layers of a photovoltaic material, e.g. CdTe or CIGS (copper-indium-gallium-selenide). CdTe cells are of particular interest given low production costs and rapidly growing market share.

Tables 2 and 3 list estimates of resource availability, resource requirements, and the resulting maximum capacity installed by 2020, 2050, 2065, and 2075 according to Zweibel (*20*), Fthenakis (*21*), and our calculations based on central assumptions in ref *21* (Supporting Information). We consider Te as the limiting component of CdTe cells, indium (In) and selenium (Se) as the limiting resources for CIGS, and germanium as the limiting resource for thin-film silicon. Cadmium is not a limiting factor for CdTe as the required amounts are a small fraction of available mining byproduct (*20, 21*).

Table 2 indicates that the maximum installed CdTe production in 2065 will be between 0.3−2.6 TW (*21*) to between 1.6−8.5 TW (our calculations) and 6 TW (*20*). Unexploited deposits that allow economically feasible mining of Te as primary material in China and Brazil could significantly decrease these constraints (*20, 21*). Nevertheless, as global energy demand grows, Tables 2 and 3 imply that CdTe and CIGS PV may not be sufficient at some point after 2030.

Such a bottleneck does not exist for silicon, the second most abundant mineral in the upper crust of the earth. Silicon can be used as either waver or thin-film; for both, considerable cost decreases are expected. In addition, new photovoltaic materials may become important; however, we emphasize that this is not necessary to overcome material constraints. The PV industry is developing very fast with many new patents, a high intensity of R&D, and significant amounts of capital invested in the exploration of new thin-film materials (*22, 23*) and "3rd generation" technologies. The latter include very low cost low to medium efficiency organic modules (*24*), very high efficiency quantum cell and nanotechnology modules (*25*), and solar concentrator systems (*26*). Given the rapidity of current development it seems plausible that at least one new option may be successful (*26*).

Third Basic Question: Are Low Prices Possible?

Past experience has shown that the rise of fossil fuels prices has usually been overestimated. Hence, hopes for renewables often faded. Now hope is high that PV will soon achieve "grid parity", i.e. a price competitive with coal electricity (*27*). This should considerably accelerate adoption of PV.

We will derive an estimate of the development of PV electricity prices (see Figure 1). The price per kWh, given in $/Wp (Watt peak: panel output during maximum insolation) depends on panel production costs. In locations with high insolation, e.g. Phoenix or Albuquerque in the U.S., a panel price of $1.00/Wp translates into 4.4 ¢/kWh levelized cost of energy (LCOE) according to Zweibel (*20*). This includes investment costs, capital, operation, and maintenance. Installation costs vary with the size of the facility. Fthenakis et al. (*7*) use data from 2007 to project module manufacturing costs of $0.70/W for utility scale plants in 2015 and $0.50/W in 2020, wholesale module prices of respectively $1.00/W

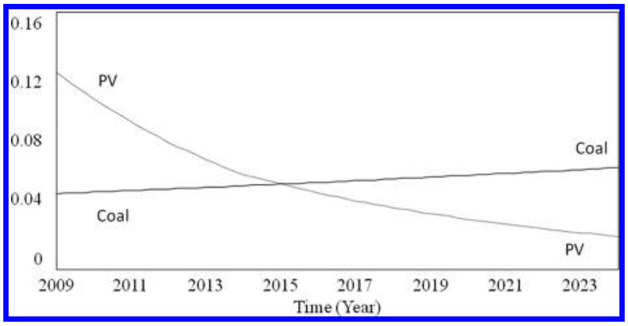

FIGURE 1. Development of the price of electricity from coal and from PV.

and \$0.65/W, and central PV plant costs of \$2.0/W and \$1.20/W−\$1.30/W. These numbers are higher than First Solar's module manufacturing cost targets of \$0.65−0.70/W in 2012 (*28*) and \$0.52−0.63/W in 2014 (*29*). First Solar has for the last several years consistently decreased its costs faster than anticipated.

Costs for production and recycling at First Solar were at \$0.87/Wp in mid 2009 (*30*). The costs of installing and connecting the panel to the grid approximately double these costs (*11, 27*). Similar cost ratios are expected for the near future with First Solar's planned reductions of 40−50% for total system costs and 35−50% for panel costs (*27*). Using Zweibel's calculation as above, 2 × \$0.87 = \$1.74 translates into 7.7¢/kWh LCOE.

First Solar does not disclose its sales price. Grossmann et al. (*31*) estimated a price of 17¢/kWh and profit rates exceeding 50% (Supporting Information in ref *31*). First Solar estimates production costs of \$0.50/Wp in 2014. If the costs for installation and grid connection decrease at the same rate, this implies electricity prices of 4.4¢/kWh, or about 5.72¢ with a more usual profit rate of 30%.

The development of the production costs achieved by First Solar cannot be fitted by a negative exponential learning curve. Costs decreased from \$3.25 in 2004 to \$0.98 in Feb. 2009, \$0.93 in April 2009, and \$0.87 in August 2009 and are projected to reach \$0.52-\$0.64 in 2014. This extraordinarily rapid decrease is due to the overlapping of two factors: a fast learning process for a technology which - as second generation PV- is still very new, and the well-known cost decrease resulting from beginning mass production (*20, 32*).

Grid parity further depends on the development of coal electricity prices. Grossmann et al. (*31*) calculated a present LCOE of 4.7¢/kWh including costs of coal of 1.33¢/kWh. The costs of coal will increase. As the rate of increase has mostly been overestimated we use the lower annual increase of 0.8% projected by McFarland et al. (*33*), starting at 1−2¢/kWh. The difference between the resulting price of 4.8¢/kWh in 2014 and the price projected by First Solar gives maximum feasible expenses for carbon capture and storage (CCS) of 5.75¢ − 5¢ = 0.7¢/kWh if no carbon taxes are levied. The International Energy Agency estimates costs from CCS of 1−2¢/kWh by 2030 (*34*). In the above scenario this implies costs of 5.8−6.8¢ per kWh, which is about the price projected for solar electricity by 2014.

However, these prices cannot be compared without considering boundary conditions. Coal-fired power plants are baseload plants which should run at full capacity at all times as their output is difficult to decrease. Since electricity prices can become negative during low demand, overcapacity in baseload is expensive. Thus flexible but much more expensive peak-load plants become necessary to meet peak-demand. Following previous analyses of peak/off-peak price differences and differences in variable electricity generation costs (*35*) we estimate that LCOE for peak-load plants are about four times higher than baseload LCOE, i.e. around 20¢/kWh.

Electricity demand in locations using air conditioning is typically highest from noon to early evening; colder locations feature a late afternoon peak with a possible secondary peak in the morning (*12, 36*). Solar power could meet the higher demand around 12−2 P.M. and in the summer until late afternoon. ST could operate at approximately 150% of the price projected for PV, i.e. 9.5¢/kWh on average and 13.5¢ per kWh in the evening with assumed heat storage costs of 4¢/kWh (*10*). This would be cheaper than peak load electricity from coal.

Fourth Basic Question: Is Availability of Land Area a Problem?

After factoring in land for coal mining, less area is required to produce electricity from solar plants in areas with reasonably high solar insolation than with fossil fuels (*7, 10, 32, 37*). Thus PV should free more land from then obsolete other energy forms than it consumes. We will discuss this in more detail for global demand and for two countries, the U.S. and densely populated Austria.

With an average insolation of 200 W per m^2 per year, 150,000 km^2 or 1.65% of the U.S. land area could meet the current U.S. energy consumption of $\sim 10^{17}$ BTU/year (*38*) corresponding to 3.3 TW (Supporting Information). With better optimized PV sites about 0.6% of the U.S. area will be needed (*39*). For Austria, we estimate that 2.62% of its land area would be needed (Supporting Information).

Current global energy demand could be met by between 344,778−767,689 km^2, i.e. 0.23−0.51% of the global land area or 0.7−1.5% of the global desert area. These fractions of land area should be easy to provide; desert areas would be highly suitable also due to few competing uses (*40*).

For future energy demand we consider economic growth at the average rate of 1970−2000 (*41*), i.e. 3.3%, for the rest of this century (subject to regional differences). This implies an 18-fold growth of the economy. With an increase of 1.6%y^{-1} in energy efficiency as above (*3*), energy demand would grow 5-fold. This increases land demand to 8% of the total area for the U.S., 13% for Austria (Supporting Information), and 1−2% globally.

Land demand also depends on energy use efficiency. PV, ST, and wind could supply electricity for EVs (*42*) with engine efficiencies >90%. Engine efficiencies of internal combustion vehicles running on gasoline or biofuel are around 30%, in addition to the overall lower efficiency of photosynthesis. The area required by biofuel and microalgae is about respectively 100 times and 10 times that needed by PV (*43*). Thus, combustion vehicles driven by biofuel or microalgae would need respectively 300 times (30 times) the area required by EVs driven by PV. This shows that in terms of area demand, PV and ST provide very interesting alternative transportation options.

Photovoltaic electricity generation requires only about 1/8 of the water needed for coal or gas electricity (*46*); no water is required for panel operation (*29, 44, 45*). PV also does not affect water quality (*44, 46, 47*). ST on the other hand requires water for cooling (*45*). Water quality impacts could occur through accidental chemical or thermal discharge. Other environmental impacts of all three technologies emphasized here, wind, ST, and PV, are very small. The toxic cadmium used by First Solar CdTe panels is hermetically encapsulated and recycled (*44*). The physical properties of cadmium, including its high boiling and melting points and water insolubility, make risks from fires, accidental breakage, or leaching extremely unlikely (*44*). Cadmium emissions from CIGS cells are also minimal compared to emissions from fossil-fuel based energy production (*48*).

We now consider the land area $L_{ji}(t). = L(r_{ji}, t)$ required in country j for the complete supply by renewable r_i at time t.

Division by the total area of j gives the percentage $F_{ji}(t)$ of land consumed at time t

$$F_{ji}(t) = 100^* L_{ji}(t) / L_j \tag{5}$$

Land demand will also grow with increasing average income due to additional demand of settlements and housing, roads, transportation, infrastructure, and dietary changes. Planning for renewable energy use will have to take this into account.

An indicator for land use requirements should further evaluate the fractions of area employed for energy generation and for natural protected area N_j. S_j describes the sustainability of country j with respect to both energy supply and land use

$$S_j = (E_j / D_j)(N_j / (k_j L_j))$$

Here E_j is the renewable energy supplied in j, D_j is the energy demand, k is the fraction of land that should be natural to reverse present environmental deterioration, and L_j is the total area of j.

S_j describes the dynamics of the trade-off between land for nature protection and energy production. Due to the multiplicative connection between the two land-use terms, S_j will approximate zero if either has a low value and will not improve significantly if the fraction of renewable energy grows while natural area decreases. Some experts describe a complete failure of nature protection with a continued decline of biodiversity in spite of nature conservation efforts. Thus, nature protection will need more area, as does energy production. This will be further aggravated by economic growth. Energy supply is more secure the more E_j/D_j approximates 1, whereas the environmental situation should improve the more $N_j/(k_j L_j)$ approximates 1. Ideal for both would be a value 1 for both terms; in this case we have $S_j = 1$.

Discussion

Additional considerations that should be prominent in any assessment but tend to be overlooked include the following. Compared to wind turbines and ST, most forms of PV do not have moving parts. Consequently maintenance is simple and cheap. The lifetime of CdTe and CIGS panels is 30 years (*48*), or more according to more recent tests (*49*). PV does not make noise and its photosensitive materials can be completely recycled (*50*). Finally, PV can be integrated into facades and on roof tops, enabling considerable additional power generation potential (*14*) and emissions reductions (*13*).

The analysis so far has shown that PV and ST can deliver the energy that is needed. With usage of silicon or further material innovation this is also true if global population grows by about 50% to 10 billion in this century (*51*), and if the economy grows 18-fold globally, implying a 5-fold increase of energy demand. As the solar potential for most countries is sufficient for a complete supply of their energy needs within their own country, this should also be a politically safe option.

In a scenario where renewable energy plays a significant role, its variability depending on time, location, and weather will need increasing attention. This variability affects wind, ST, and PV (*12, 52, 53*). To supplement our discussion we summarize a few recent results on systemic solutions for this problem. Systemic solutions combine different forms of renewable energy (*54, 55*) and different locations of energy generation in a portfolio approach to minimize outage times (*14, 56*).

Connecting several locations into a geographically diverse array decreases given outage times and buffers against the variability of individual sites (*7, 54–57*). Connecting the four time zones of the U.S. extends the time available for solar electricity generation by four hours, while a north–south connecting network decreases the impact of reduced daylight hours in northerly latitudes during winter and allows the south to benefit from the much longer daytimes during summer in the north.

Palmintier et al. (*54*) determine optimized portfolios out of 8 U.S. solar and 35 wind sites. They find a 45% reduction in wind energy output variability and a 15% reduction for solar energy compared to the average of individual sites. In a combined optimized portfolio drawing upon 8 solar and 35 wind sites, Palmintier et al. (*54*) find a 55% reduction in variability. Marked improvements are already achieved with a small number of suitable sites (*54*). An extended network capable of transmitting large quantities of solar electricity could be based on 500 kV HVDC (high voltage direct current) technology with lower losses and costs than older AC-based systems (*12*). This would require research and development investments as well as national planning.

A third component of a systemic solution is energy storage with technologies such as molten salt for solar heat, compressed air energy storage (CAES) for both solar and wind (*10, 12*), or hydrogen and EVs (*58*). Concentrating solar power (CSP) plants can be designed to either individually store heat with molten salt until well into the next day (*59*) or as part of a group of geographically dispersed plants that allow 24 h electricity supply (*7*). Present storage costs are at 3–4¢/kWh (*10*). These costs should decrease over time. For base-load PV plants equipped with CAES, costs of 11.8¢/kWh in 2020 have been estimated (*12*).

Surplus electricity from renewables could also be stored with EVs that feed electricity back during high demand (*10, 42, 57, 58*). We estimate that 200 million EVs could store about 5% of the U.S. daily energy consumption (Supporting Information). This should cover a reasonable fraction of the energy needed during those times at night when wind power is not available. Peak prices can also be reduced through grid balancing with intelligent grids (*57*) that use information on hourly electricity use to allow demand response (*60*).

Based on the indicators given above, a systemic configuration could look as follows. A major proportion of electricity could be generated by PV; some would be stored in EVs. ST would be used mainly for heat storage and when PV and wind do not suffice. Adding wind energy could reduce power output variability by 60% relative to the optimal solar configuration (*54*). In particular, wind energy would be used at night. Surplus wind could be stored with technologies such as CAES or hydrogen.

Overall, the indicators show that PV and ST are able to become the quantitatively most important energy source. They also show that PV is evolving rapidly but has a long way to go to fulfill this role. This is in accord with earlier evaluations (*10, 11*). The next few years will decide whether PV will play this role. The indicators presented allow an early assessment of the development along this path.

A further conclusion is that area is becoming critically scarce in many countries and with regards to all forms of energy. We have provided an indicator to evaluate sustainability and the proportion of energy supplied by renewable sources in conjunction. This indicator could help inform necessary future research on new land use strategies vis-à-vis growing area demands.

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Supporting Information Available

Additional text and tables. This material is available free of charge via the Internet at http://pubs.acs.org.

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