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Implications of diurnal and seasonal variations in renewable energy generation for large scale energy storage

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Large scale implementation of solar and wind powered renewable electricity generation will use up to continent sized connected electricity grids built to distribute the locally fluctuating power. Systematic power output variation will then become manifest since solar power has an evident diurnal period, but also surface winds—which are driven by surface temperatures—follow a diurnal periodic behavior lagging about 4 h in time. On an ordinary day a strong diurnal varying renewable electricity generation results when combining wind and solar power on such continent sized grid. Comparison with possible demand patterns indicates that coping with such systematically varying generation will require large scale renewable energy storage and conversion for timescales and storage capacities of at least up to half a day. Seasonal timescales for versatile, high quality, generally applicable, energy conversion and storage are equally essential since the continent wide insolation varies a factor ∼3, e.g., in Europe and Northern Africa together. A first order model for estimating required energy storage and conversion magnitudes is presented, taking into account potential diurnal and seasonal energy demand and generation patterns. A few scalable energy storage methods are briefly indicated. [http://dx.doi.org/10.1063/1.4874845]

INTRODUCTION

Dominant resources for renewable electricity generation are solar and wind power. Solar power is generally seen as having the largest global technical potential[1,2] while the latter is on an implementation track leading to a significant percentage of the global electricity production. In 2012, close to 280 GW installed wind power is reported worldwide and forecasts indicate up to 100% growth between 2011 and 2016.[3] In many countries GW installed power wind parks are being built or planned for installation in the next decade amounting to several tens of percents of the average electricity generation. By 2050 as much as half of the current total energy use (∼525 EJ/year) may be generated by solar and windpower alone (∼270 EJ/year).[1,2] These solar and wind power generating capabilities are grid connected in order to transport energy from (on/offshore) harvesting to utilization site. Depending on operation level, these grids can operate locally in the distribution grid or on larger scale in the high voltage transmission grid. In addition, long distance grid connections are becoming available and are being considered to extend over several thousands of kilometers, e.g., from north west Europe to northern Africa, or across USA and Canada. The rationale behind such large sized grids is to enable trade and transport of power, and to secure energy supply by averaging the local fluctuations in the instantaneous generated solar and wind power over extended areas. But what systematic variation in time of the output power of extended grids can be expected? And how can one cope with the variation, using energy storage on what scales? Here a model is presented to enable to make such estimates.

Depending on technological development and actual deployment the solar power generation resources are generally seen as having the potential to power the world, since about 7400 times the amount of solar energy reaches the earth's surface as what may be required for societies energy use (about 122 000 TW solar radiation reaches the surface of the earth while society uses about 525 EJ/yr[1] = 16.6 TW, i.e., 122 000/16.6 = 7.4×10^3). The harvesting technologies include thermal methods such as concentrated solar power (CSP) and solar collectors, and photovoltaic (PV) methods (solar cells). In general the thermal methods use the heating of a working liquid to high (CSP) or moderate temperature and heat is extracted either to generate electricity or use it as direct heating. PV has electricity as output directly.

The insolation (solar radiation power per square meter at the earth's surface) is daily modulated between zero and a maximum that depends on the latitude on earth and the season (Figure 1). For instance in Edmonton in Canada, Delft in the Netherlands, and Astana in Kazachstan (∼52° North), there is a factor of 6 between the insolation in mid summer and mid winter due to the reduced instantaneous light intensity and time of daylight (Figure S1[4]). In Mexico City, the Western Sahara and Nagpur in central India (∼19.5° North), the factor between summer and winter reduces but still reaches a sizeable factor ∼1.5. Thus in principle a factor of 6 to 1.5 difference per solar power collecting footprint between seasons occurs, next to the diurnal day and night fluctuations, and varying cloud covers. These seasonal and diurnal influences multiply with each other to obtain the total solar power. For a multi Tm^2 (Terra $\text{m}^2 = 10^{12}\ \text{m}^2 = 10^3 \times 10^3\ \text{km}^2$) grid connected surface area spanning Europe and Northern Africa this will mean on average a

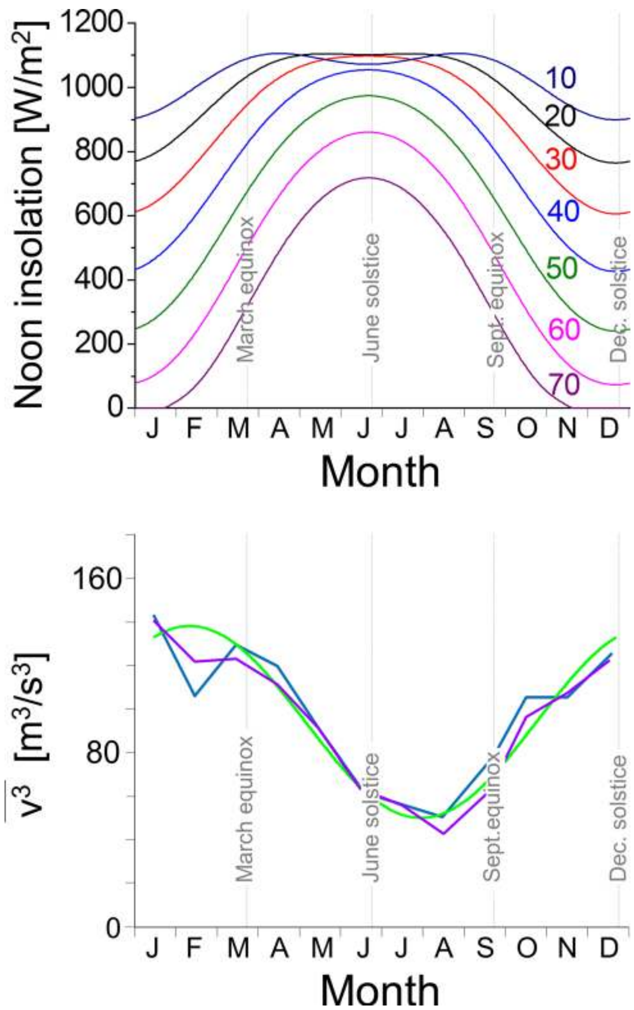

FIG. 1. Top: daily insolation at noon during the months of the year on the indicated northern latitudes. See also Fig. S1 in the supplementary material[4] for the total daily insolation. Bottom: estimated average cubed windspeed v^3 in the US for on shore (blue) and off shore (purple) locations (based on data from Ref. 5), and a simple sinusoidal approximation as in Eq. (2) (green).

sizeable factor ∼3–4 between summer and winter insolation, modulating the day and night diurnal variation on a seasonal scale.

Wind resources within a continent sized electricity grid depend on the instantaneous wind speeds averaged over the grid surface area. It is well known that the wind power is about two times stronger in winter than in summer on northern latitudes (Figure 1).[5] Next to this seasonal timescale there is however also a diurnal periodicity of relevance. In meteorological literature a number of data studies are available of the near surface layer average wind speeds over extended surface area's in Africa and the North Atlantic,[6] and the US[7] in which thousands of local weather stations have been taken into account. The general insight gained is that there is a diurnal variation in wind speeds with significant amplitude, where the peak in wind amplitudes occurs in the afternoon and the minimum 12 h earlier in the early morning. For instance in Ref. 7, the instantaneous wind speed averaged over a $\sim 800 \times 1000$ km^2 surface area on an ordinary day could be 4–5 m/s while the minimum could be 2 m/s (Figure 2). The wind speed amplitude has such diurnal pattern because it is driven by the surface temperature, i.e., the solar radiation heating the surface and atmosphere above it drives the observed wind speeds. Also more local studies in Mexico,[8] UK,[9] Scandinavia,[10] Sicily,[11] and Grenada[12] report these diurnal wind patterns. Since the kinetic energy contained in flowing air scales with the third power of the wind speed a factor 2 in wind speed amplitude means a factor 8 in recoverable energy in wind turbines.

Future wind energy implementation will also include more off shore wind parks preferably in shallow sea waters which will often be in national waters near the coastal line. In 2011 4.1 GW of the installed power was located offshore.[3] The wind patterns and diurnal variation in those is determined by the significant differential heating of the water and land area. During the day the land warms relatively fast due to solar light absorption and the cooler and denser air from the adjacent ocean flows over the land.[13] At night the land cooling takes place by the continued emission of infrared radiation and the air flows reverse. Since the infrared is absorbed in the atmosphere more readily than the visible light (which is the basic origin of the Greenhouse effect) the nightly cooling process is on average relatively slower and the near coastal winds during night are therefore also driven less powerful than during daytime. Quantitative measurements on these diurnal ocean winds have been performed on a global scale using data from the NASA QuikSCAT satellite scatterometer launched in 1999.[13–15] The sea breeze can extend several 100 km into the sea which means that the (future) wind turbines in those regions are under the influence of such diurnal wind patterns.[14] It is also noted in Ref. 13 that in winter time the temperature difference between land and ocean is reduced and the sea breeze largely disappears.

Here a model calculation for solar power plus wind power on extended area power grids is presented. The diurnal and seasonal variation of the solar and wind power contributions add up in this model, and together they show the total renewable power variation on diurnal and

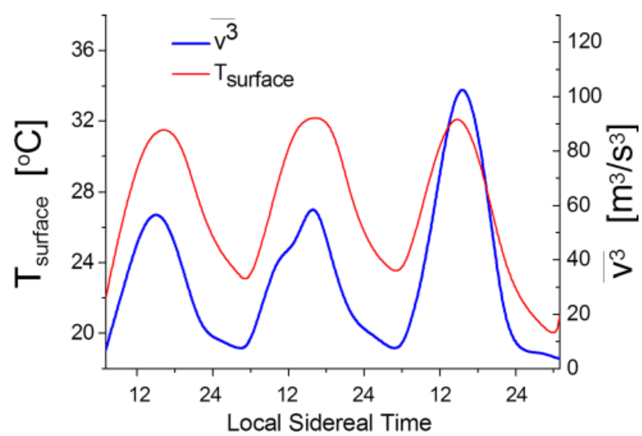

FIG. 2. Daily averaged v^3 for a large 800×1000 km^2 area in the US and the average surface temperature for three consecutive days (constructed from data in Ref. 7).

seasonal timescales. Clearly there have to be made simplifying approximations in such global approach. The obtained generation patterns are compared with three different renewable solar and wind power demand patterns in order to make a first estimate for the demand of future energy storage scales. The technical features of this model approach are described in the Methods section below.

METHODS

The estimation of the integral number for future solar and wind power generation in future years is taken from Refs. 1 and 2. This is the prognosis for the total globally generated energy using these respective techniques during a selected year. The Global Energy Assessment (GEA) 2012 has been made with support by many national and international organizations; however, the values remain a prognosis. These numbers cited are in EJ/yr, i.e., there is no time structure of the output power during the day and year. To come to such time structure for solar power the geographical location of the different generating facilities connected to the large scale power grids needs to be taken into account; the insolation on a particular latitude θ_L of the earth surface varies due to the daily and seasonal varying zenith angle and the length of day. Taking the position of installed solar power at the geographical latitude θ_L and longitude φ into account, the variation $\mathrm{I_{solar}(t)}$ throughout the year becomes

$$
\begin{aligned}
\mathrm{I_{solar}(t)} &= \max\left\{ I_{solar}^{total} \sum_{\theta_\mathrm{L}=-90}^{90} \sum_{\varphi=-180}^{180} G_{solar}(\theta_\mathrm{L},\varphi)\frac{\mathrm{Cos}(\theta_\mathrm{L},\varphi,t)}{F(\theta_\mathrm{L},\varphi)} \right. \\
&\qquad \left. \times\left(a_0 + a_1\exp\left(-\frac{k}{\mathrm{Cos}(\theta_\mathrm{L},\varphi,t)}\right)\right), 0\right\}, \quad \text{in EJ/day, where} \\
\mathrm{Cos}(\theta_\mathrm{L},\varphi,t) &= \sin\theta_\mathrm{L}\sin\delta(t) + \cos\theta_\mathrm{L}\cos\delta(t)\cos\left(2\pi\left(t-\frac{1}{2}\right)-\varphi\right), \\
\delta(t) &= \delta_0\cos\left(2\pi\frac{(t-172)}{365}\right), \\
F(\theta_\mathrm{L},\varphi) &= \int_0^{365}\mathrm{Cos}(\theta_\mathrm{L},\varphi,t)\left(a_0+a_1\exp\left(-\frac{k}{\mathrm{Cos}(\theta_\mathrm{L},\varphi,t)}\right)\right)dt,
\end{aligned}
\tag{1}
$$

where I_{solar}^{total} equals the total integrated energy generated by solar power in a year, and δ_o is the declination angle of 23.45° of the earth rotation axis. The term between brackets with parameters $a_0 = 0.4237$, $a_1 = 0.5055$, and $k = 0.2711$ stems from the transmission of solar rays through the standard clear air at sea level.[16] The $\mathrm{Cos}(\theta_L,\varphi,t)$ is the reduction of solar power due to the angle the solar rays make with the earth surface throughout the year at latitude θ_L and longitude φ, while $F(\theta_L,\varphi)$ is a normalization factor that makes that the total solar energy generated during the year adds up to the number I_{solar}^{total}. The factor $\cos\left(2\pi\left(t-\frac{1}{2}\right)-\varphi\right)$ is resulting from daily rotation of the earth with the hour angle, while the function max{ … ,0} imposes that no negative values for solar radiation amounts can result at night or in winter. The fraction of the solar power facilities connected into the grid at the location (θ_L,φ) is represented by $G_{solar}(\theta_\mathrm{L},\varphi)$.

For the generated wind power a dependence on the day t of the year is approximated to match the numerical experimental data in Figures 1 and 2 as

$$
\begin{aligned}
\mathrm{I_{wind}(t)} &\approx \frac{\mathrm{I_{wind}^{total}}}{365}\sum_{\theta_L=-90}^{90}\sum_{\varphi=-180}^{180} G_{wind}(\theta_\mathrm{L},\varphi) \\
&\quad \times\left(\cos\left(2\pi\frac{(\mathrm{t}-29)}{365}\right)\frac{43}{92}+1\right)\left(\frac{3}{4}\cos\left(2\pi\left(t-\frac{16}{24}\right)-\varphi\right)+1\right),
\end{aligned}
\tag{2}
$$

in EJ/day. The second cosinus term approximates the diurnal wind power variation from Figure 2; it peaks at 4 h past midday at the longitude φ. $G_{wind}(\theta_L, \varphi)$ is again determined by the locations of the wind power facilities. The seasonal time dependence of the solar (1) and wind (2) contributions has different amplitude and phase shifts.

Clearly large uncertainties remain in the future solar and wind power implementation rate and geographical locations. However, this approach can easily be refined when new implementation data become available while the nature of the variations with time remains the same.

To come to a magnitude of the energy storage demand apart from the generating capabilities, the demand side on the short daily and the long seasonal timescales has to be taken into account. The total energy use and electricity use is relatively constant throughout the year (increasing each year[1]), although it shows a larger demand in mid summer (air-conditioning) and mid winter (heating and lighting) in for instance the USA.[17] The daily energy demand shows a night time low and a morning and afternoon peak as illustrated using various available energy use data in Ref. 18, the electricity demand shows a pattern which varies much less strong.[18] To model these demands $D_{total}(t)$ numerically the following equations were used:

$$D_{\rm total}(\rm t) = P_{\rm total}(\rm t) - P_{\rm Electricity}(\rm t) + E_{\rm total}(\rm t), \tag{3}$$

where

$$P_{\rm total}(\rm t) \approx \frac{P_{2050/30}}{365} \sum_{\theta_L=-90}^{90} \sum_{\varphi=-180}^{180} \left[P_{Summer}(\theta_{\rm L}, \varphi, t) \left(\frac{1}{2} + \frac{1}{2} \cos\left(\frac{2\pi(t-172)}{365} \right) \right) + P_{Winter}(\theta_{\rm L}, \varphi, t) \left(\frac{1}{2} - \frac{1}{2} \cos\left(\frac{2\pi(t-172)}{365} \right) \right) \right] A(t), \tag{4}$$

where $P_{Summer/Winter}(\theta_L,\varphi,t)$ is the intraday primary energy demand having a pattern as in Ref. 18 (a numerical approximation is given in the supplementary material[4]). Here as an approximation the hour angle φ follows integral multiples of 15° since the energy use will be related to the time in individual time zones. As a further refinement the hour angle φ could be chosen according to the actual longitudes of a country (which is not done here). The 172nd day is the 21st of June. The function $A(t)$ has the form: $A(t) = (1 + 0.075\cos(4\pi(t-217)/365))\ (1 - 0.045\cos(2\pi(t-217)/365))$ and approximates the variation in primary energy use throughout the year as observable in Ref. 17 (peak in winter and lower peak in summer). The electricity demand $E_{\rm total}(t)$ has the same form of equation as (4) but now with $E_{\rm Summer/Winter}(\theta_L,\varphi,t)$ replacing $P_{\rm Summer/Winter}(\theta_L,\varphi,t)$ and $A(t) = 1$. $P_{Electricity}(t) = E_{\rm Total}(t)/0.50$ is the primary energy required to generate the electricity $E_{\rm Total}(t)$ assuming a 50% efficiency; it has thus the same time dependence as $E_{\rm Total}(t)$. 50% efficiency is lower than what can be reached in modern gas fired combined cycle power stations; however, this choice accounts for the use of, e.g., lower efficiency coal fired power stations as well. It is subtracted in $D_{Total}(t)$ to come to an energy demand which is usable energy for the end consumer, and in order to be able to subtract the renewable electricity from the fossil based electricity.

A second factor that is important to determine a future energy storage scale is the connectivity of the generating facilities on large extended power grids. This determines how much electricity from distant sources, transmitted at the speed of light through the electricity grid, contributes to the instantaneous integrated output of the grid. The plans for long distance power transport include connected grids on the size of, e.g., Europe plus northern Africa; i.e., latitudes from ~24° to 62° and distances $\sim 2000 \times 3000$ km^2. Much larger grids are not considered in view of the large cost and increasing transport losses; the cost will increase faster than linear with distance traveled since also the amount of peak power to be transported will grow with the surface area that is connected. This distance constraint makes that here a calculation for a large but limited range of latitudes and longitudes is considered. The result can, however, be extrapolated to the worldwide generating capabilities and storage demands because other independent grids will mostly be located on similar latitudes.

The future electricity demand will be modeled according to three different scenarios. Scenario I is having the year average electricity demand scaled up with the same factor as the total energy is scaled up. Scenario II is having a year average electricity demand scaled up to the total yearly renewables generation, and Scenario III is having the same electricity demand as Scenario I but added to that a demand contribution having the time structure of the primary energy demand. The total year average demand in Scenario III equals the yearly renewables generation. Scenarios II and III thus indicate the electrification of previously fossil powered demands in two different ways. Having the demand and supply characteristics modeled as described above, the storage requirement on different timescales can be estimated from the difference between the demand and the supply during chosen periods of time. The formulas used here are in the Supplementary material.[4]

RESULTS

Renewable power variation on continent sized grids

To obtain numerical values for the solar and wind power during the year Eqs. (1) and (2), respectively, are applied. The amplitudes $I^{total}_{solar,wind}$ are taken from estimated mean global values in the GEA 2012 report.[1] For comparison also a mean value from the Intergovernmental Panel on Climate Change (IPCC) 2012 report[2] is shown. The values used for (I^{total}_{solar},I^{total}_{wind}) are from the GEA-Mix/IPCC-Median estimates: (70,40)/(2.2, 11.3) EJ and (170,80)/(12.8, 23) EJ for 2030 and 2050, respectively. It should be noted that the IPCC number used stems from the median of a large number of separate studies with a very large spread in the predictions. The GEA-Mix values are significantly higher than this IPCC-Median but are still within the ranges considered by the IPCC report. Since the GEA-Mix report is aimed at specifically energy forecasting, we use these values in the remainder; however, the IPCC values are used to produce the indicated graphs for comparison. The modeled power outputs are in Figure 3 (averaged over a day), 4 (instantaneous) and S2, S3, S4[4] graphs for an extended power grid. The range of latitudes for the grid used here as an approximation is between 20° and 60° with $G_{solar,wind}$ $(20°,\varphi) = 5\%$,

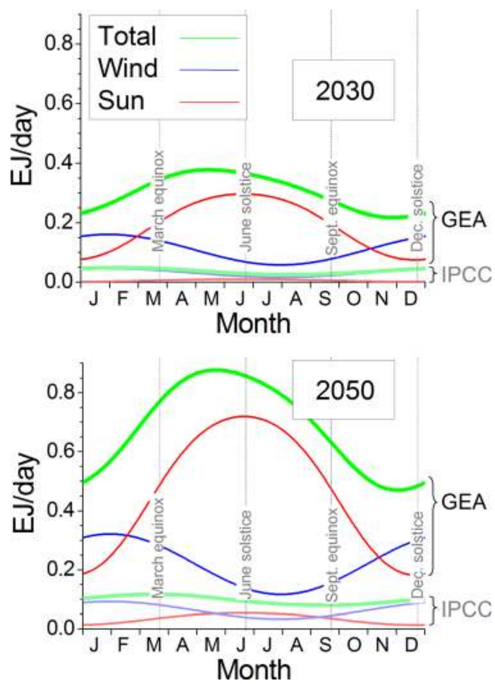

FIG. 3. Estimated output per day of wind and solar power in the months of the years indicated. Due to the geographical locations of the facilities above the equator (see text) a significant variation in output power throughout the year is expected. GEA and IPCC (lower curves) indicate two different levels of renewable energy implementation.

$G_{solar,wind}$ $(30°,\varphi) = 15\%$, $G_{solar,wind}$ $(40°,\varphi) = 35\%$, $G_{solar,wind}$ $(50°,\varphi) = 35\%$, and $G_{solar,wind}$ $(60°,\varphi) = 10\%$. The average latitude is then 43°, which thus assumes that the solar power installations are considerably more south than currently. In addition equal contributions of a longitude −5°, 5°, and 15° were taken corresponding to about 1600 km in the east-west direction. Such range of latitude and longitude corresponds roughly to grids spanning Northern Africa to Europe, and it is also within the latitude range where, e.g., the high density population and energy use is of the USA, North/East India, and China. The majority of installed capacity may be anticipated in such latitude range, e.g., to minimize transport costs and crossing of state borders.

Energy demand patterns

The energy use is modeled according to available current demand patterns throughout the year for electricity and primary energy. The assumption is that much of the current and future demand is, and will be, organized in time for functional reasons that cannot easily be altered to a large extent, but the use of electricity relative to primary energies can be altered. To obtain numerical values for time dependent demand patterns an approximation of known data is used as described in the Methods section. In Figure 4(a) the estimated demand patterns for the 21st of each month are given for electricity and primary energy from which the primary energy (mainly fossil fuels) required to generate electricity has been subtracted. The ratio primary energy to electricity demand is initially simply kept constant at the current ratio while both are scaled up to reach the future total energy use level in the GEA-Mix scenario (demand type scenario I). Comparing the instantaneous electricity demand with the sun + wind generating capabilities in Figure 4(a) and 4(b) immediately shows that by 2050 the instantaneous electricity demand in this scenario I will be significantly lower than the instantaneous renewables generation during

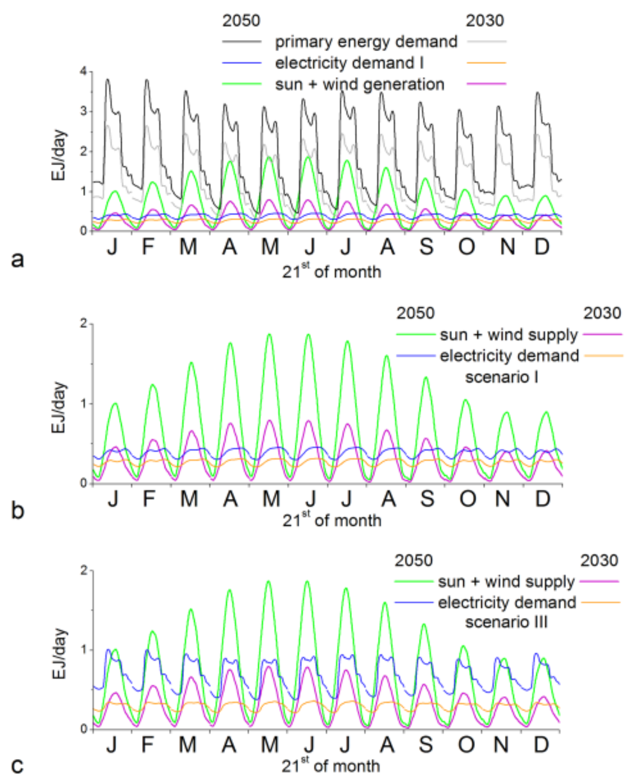

FIG. 4. (a) Estimated output from the model grid on a selected latitude and longitude distribution (see text) for 2030 and 2050 during the 21st of the months indicated, scaled up to world scale and using the GEA-Mix implementation of renewables. Also the total energy use and the electricity use in scenario I are indicated. The renewable energy demand patterns I and III are included in Figures 4(b) and 4(c), respectively.

most of the day, even in winter. To make use of the renewable power will thus necessitate (1) conversion of applications to use electricity instead of primary energies where that is possible, and (2) realize sufficient electricity supply throughout the year to power these additional electric applications, or alternatively (3) directly convert the renewable power to a form of primary energy that can be accepted by applications using primary energy from fossil or renewable origin. This may include the use of solar heat directly in combination with storage when possible. In principle, conversions of electricity to other primary energies involves losses; for that reason direct use as electricity—if possible—is of advantage.

(1) and (2) denote that the year average electricity demand will be best of the order of magnitude of the average renewable electricity generation to minimize the amount of conversion losses. Coping with the summer daytime peak and lower output during winter and at night will mean partly storing the peak electricity supply from renewables for use at night and in winter. On seasonal timescales, this involves renewable electricity conversion into a suitable form of stored primary energy or fuel. The same conversion to a suitable primary energy is also the case in (3), but then without the long term storage. In Figure 4 there are therefore two demand scenario's given: scenario I which has the pattern of the electricity demand scaled up to a year average demand increased by the same factor as the total energy demand is increased, and scenario III with the electricity demand as in I, but added to that an additional primary energy demand pattern bringing the total year average demand to the year average renewables generation level. Scenario II is the demand pattern similar to I, but then scaled up to reach the year average renewables generation, i.e., increased more rapidly than total energy use (Figure S3[4]).

Energy storage and conversion scales

To cope with the described systematic variability of renewable electricity generation, the current approach is to power up and down fossil fuel powered stations. In this way renewables reduce the operational filling factor of these stations, have an impact on the business model of these facilities, but do not really replace fossil fuel generating capabilities. The additional storage capacity required then "only" covers the time it takes to power up or down the fossil fuel powered stations to maintain the grid stability, if possible. From the modeled daily output by 2050 in Figure 4 it is clear that coping with the renewables peak power by switching off fossil power alone is not enough, since significantly more renewable power is produced than can be switched off. Thus assuming that renewable power generating capabilities essentially *should replace* fossil fuel based power generating capabilities *and* electricity will be converted to primary energy forms like fuels this will necessarily represent renewable energy storage and conversion on an unprecedented scale. The dependence on fossil fuel and the associated CO_2 emission can then be reduced as illustrated in Figure 5.

The demand for renewable energy storage and conversion is estimated as follows. First, the daytime renewable electricity generation which is larger than the demand is stored for later use in the night, leading to a short time storage demand. Note that such short term storage also includes load or demand time shifting of, e.g., electrical vehicles. The remaining surplus of renewable energy is assumed to be converted to primary energy (e.g., high energy density fuels, see below) and stored for the longer seasonal timescale. Using this approach Figure 6 results for the magnitude of short and long term energy storage demand. In Table I the short and long term storage for scenarios I, II, and III is summarized. Clearly long term storage only takes place in summer, and this is in this approach completely used up in winter. Short term storage would still occur in winter when the instantaneous generation is larger than the instantaneous use of renewable power. The result is that scenario I would generate the need for significantly more short and long term storage capacity, essentially because the demand is too low compared to the generation. In scenario I in fact more energy is stored in summer than can be used in winter to generate electricity. Scenarios II and III will thus be more realistic and favorable, since the renewable energy generated is also completely used (with or without storage/conversion). There is not so much difference between the latter two scenario's with up to 0.2 EJ/day

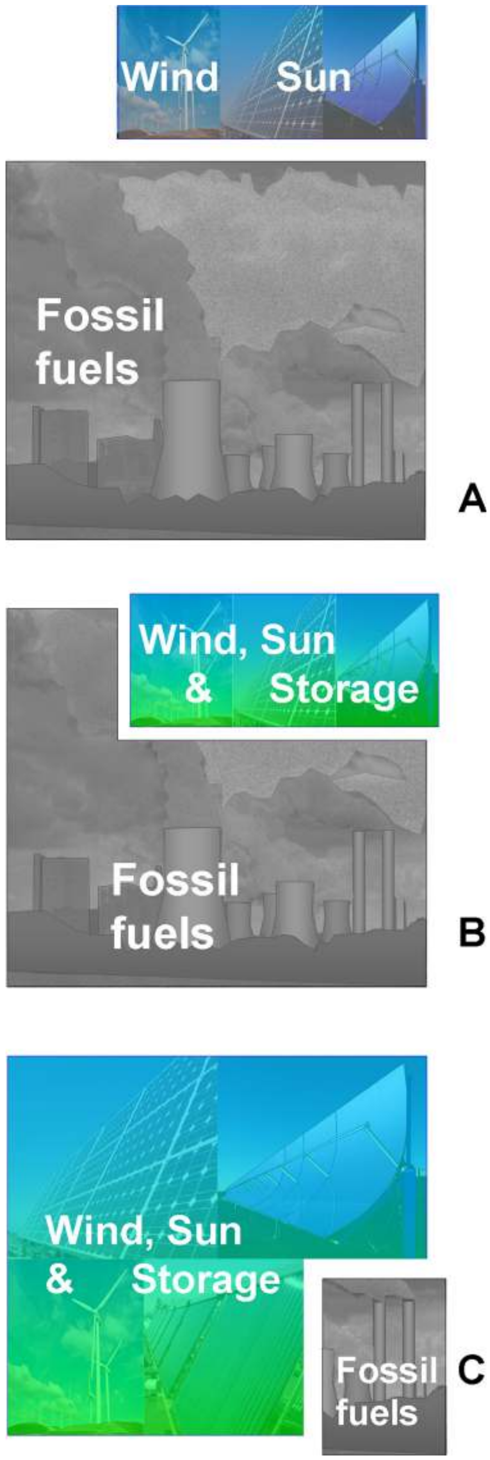

FIG. 5. Schematic of installed rated power. (a) Fossil generating capabilities and renewable solar and wind power without renewable energy storage option. To guarantee security of supply practically the full conventional fossil capacity will be required. (b) and (c) With long and short term storage of renewable energy part of the fossil capabilities can be replaced progressively by renewable powered facilities, or be fueled with renewable fuel.

short term and around 30 EJ = 8333 TW h per season long term storage by 2050 worldwide. This corresponds to 20 days of current primary energy use in the GEA prognosis for 2050 (∼525 EJ/365 = 1.4 EJ per day). The short term storage then corresponds to about 0.7% of the

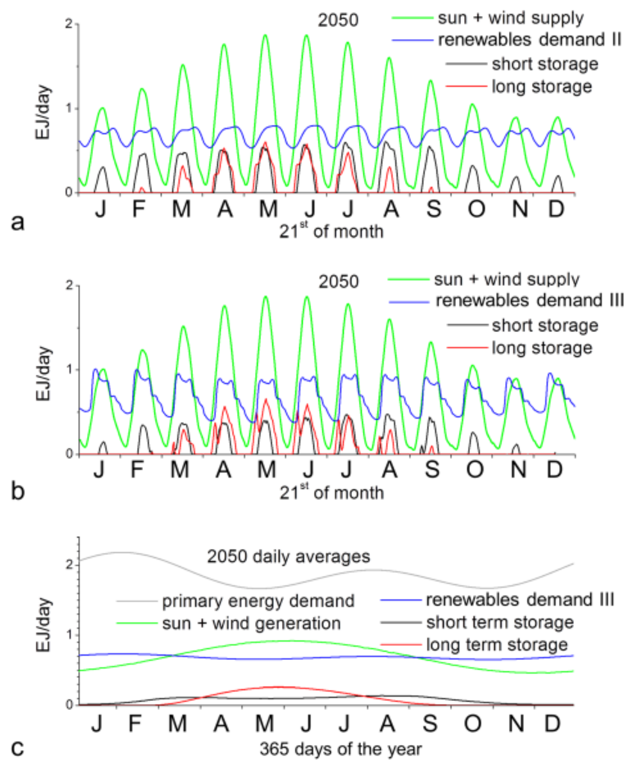

FIG. 6. The pattern of renewable energy storage during the indicated days of the year 2050 in scenarios II (Figure 6(a)) and III (Figure 6(b)) for the grid on the Northern hemisphere as indicated in the text, and scaled to the total world electricity and energy use. The integral values for 1 day in (c); the primary plus the renewable energy demand equals the total usable energy demand.

seasonal storage, and on average ~8 kWh installed storage capacity per person on an earth with 7×10^9 inhabitants.

DISCUSSION

The solar and wind power generation on large scale grids will vary strongly and systematically on both a daily and seasonal timescale. The comparison with the demand for energy during the day and seasons, results in significant storage demands on different timescales if one intends to completely use the energy that is generated. As far as we know this is the first such global scale estimation. At the same time, the different prognosis of solar and wind power implementation of GEA and IPCC reports illustrate that the actual range of storage requirements can vary significantly. Also in the model for the time dependent demand choices are made that can influence the storage scale. However, the method used can be easily adapted when the implementation of solar and wind power as well as the demand patterns progress in the coming decades. Additional sources of discrepancies will be the variation of the extended

TABLE I. Summary of energy storage demands in demand scenarios I, II, and III, based on the model described and GEA prognosis for average renewable energy generation in 2030 and 2050.

	Short term storage demand 10^{-2} EJ/day		Long term, seasonal, storage demand, EJ	
Demand scenario	2030	2050	2030	2050
I	2–8	5–9	16.5	108
II	2–9	3–20	10.7	27.5
III	1.5–8	1–14	10.8	29.2

weather conditions from day to day and season to season, e.g., a cold winter or hot summer will have an impact on the energy use and generation in sections of the world. In that sense we used averages of the weather and absorbed all local and temporal fluctuations that will be present in reality. In practice, however, one can propose that this will rather increase than decrease the demand for short term and long term storage, since the stored energy also provides partial independence from adverse renewable energy generation conditions.

In the solar radiation estimation we did not take into account the orientation of solar panels towards the sun, but rather used the W/m^2 horizontal surface. This simplification was chosen since in practice many PV panels on, e.g., roofs will not have the ideal orientation and because then also shadowing effects may be taken into account. The effect of this approximation will have some influence on the shape of the daily solar power generation curves, but since the total generated solar energy is normalized not on the total yearly solar power generation.

More extended grid scale, extending towards the southern hemisphere would address the summer winter variability, while even larger east-west grids also spanning the entire globe would also address the day and night variability. However, the feasibility of such power harvesting and grid is not beforehand clear in view of geographical factors such as available land area, depth of oceans, and geopolitics. Also the losses for each 1000 km may be 3% for high voltage DC lines,[19,20] the AC-DC conversion, and back taking an additional 1.5% each. For distances up to 20 000 or 30 000 km the transmission then amounts to $0.985^2 \times 0.97^{20\text{ or }30} = 0.53$ or 0.39. In addition, such very long distance grid should transport not on GW scale, as local power grids are currently built for, but rather on the level of power use of a continent, i.e., TW scale, which will also make it highly costly, if feasible. Thus also with such investment in a world grid, losses are non-negligible (and cannot be reused). For less long distances, e.g., the distance from Norway to the Sahara ($\sim$4100 km), smaller losses occur (transmission = 0.86), but as stated above the daily and seasonal storage are not addressed. Counteracting seasonal effects could be possible with a grid extending from Norway to below the equator (e.g., Angola) which is a distance of 9300 km (transmission 0.73), but then the day and night variability is not addressed.

The solar power generation as estimated above is located on the northern hemisphere where the largest part of the human population is located. For the southern hemisphere the same energy generation and storage scheme can be used, but then shifted 6 months and 12 h in time. Since the power grid will not be connected over such long distances the global energy storage requirements will be similar, proportional to the overall installed capacities. The method used here adds all generation, use, and storage shifted to one central time, effectively adding up to a world wide contribution.

For smaller grid scales in principle, the weather conditions become less averaged and more fluctuating, and also more dependent on the specific location. The "short term" storage facilities then likely needs extension of the capacity towards storage times of days in order to deal with several unfavorable renewables generation days. The seasonal scale will depend on the more local average climate.

Based on the above both short term daily and long term seasonal storage is required on scales that will only be feasible for few storage options.[21–23] Important scalable options for short term storage are heat storage[24] (high temperature storage for CSP, low temperature heat) and batteries[25] (sun-PV, wind). Currently applied pumped hydropower relies on the presence of suitable geographic factors and is thus limited in scale. The use of batteries as electricity store will require low cost and far improved lifetime during prolonged cycling of the batteries; an energy store may be built for at least 20–30 years continuous use (10^5 h) compatible to, e.g., PV lifetimes. For seasonal scale energy storage artificial fuels are required. Hydrogen can be produced from renewable electricity and water[26,27] using, e.g., alkaline electrolysis with relatively inexpensive Ni based catalysts. Ammonia stands out in energy density for static stores as it is liquid at 10 bars and room temperature (RT) with an energy density of 22.5 MJ/kg higher heating value (HHV), and it contains only abundant H and N.[28,29] More conventional fuels with highest energy density up to 49 MJ/kg (propane) would require carbon, but can in principle be generated from renewable power, water and CO_2 using existing technologies.[30] However, ultimately in a fossil fuel poor energy economy CO_2 has to be captured from air since central point sources would produce only a fraction of the needs.[31]

BIOFUELS FOR LARGE SCALE STORAGE?

In Refs. 26 and 32, the use of biomass for biofuel generation is essentially excluded as viable large scale option. In the IPCC report,[2] however, it is indicated with large uncertainty that biomass could contribute between 10% and 100% of future energy use. To gain some insight in this matter we use recent estimation of the energy production from biofuels per year to come to a surface area that would be required for producing chosen amounts of biofuel. As a reference the current energy use is expressed in required production of ml oil/m^2 of earth surface and biofuel production in terms of oil equivalent per m^2 earth surface (Fig. 7).

With a higher heating value of 34 MJ/l (gasoline) and an earth total surface area of 5.1×10^{14} m^2 the current energy use of ∼500 EJ/yr equals 28.8 ml oil/m^2; an oil film of 28.8 μm thick on the entire globe (Fig. 7). One of the often mentioned high yield biofuel sources that would not compete with food production directly is switchgrass. Its net energy yield in the form of bioethanol is reported[33] as 6 MJ m^{-2} yr^{-1} which is equivalent to 176 ml oil $m^{-2}yr^{-1}$ (heating value of ethanol is 23.43 MJ/l). In order to power the world with switchgrass bioethanol one thus requires at least $28.8/176 = 16.3\%$ of the entire surface of the globe, or ∼half of the land area (assuming appropriate climate conditions). For poplar trees the result is similar.[34] For biodiesel from palmoil an estimated 0.6 l m^{-2} yr^{-1} is reported. In general for biodiesel 2.2 units of oil are the net energy gain for a harvest of 3.2 units,[35] i.e., $600 \times 2.2/3.2 = 412$ ml m^{-2} yr^{-1} is the gain. So for palmoil $28.8/412 = 7.0\%$ of the earth surface would be required to produce 500 EJ/yr. These numbers are relative to the entire surface of the globe, including oceans, poles, deserts, permafrost and mountains, regions with wildly different and incompatible climate conditions. The current agricultural area is quoted as 49×10^6 $km^2 = 4.9 \times 10^{12}$ m^2 in 2010 by the Food and Agriculture Organization of the United Nations, which is almost 1% of the earth's surface area. For switchgrass and poplar, and palmoil thus 16, respectively, 7 times more than the current agricultural area would be required to produce sufficient biofuel to reach the higher limit of 500 EJ/yr. In such perspective 10% of that appears as an enormous amount of additional area which needs to be made accessible for agricultural activities in a sustainable manner. In addition the biomass will need to act as a valuable carbon source for materials fabrication and as such may become too precious as fuel.

Biofuels could also be considered to cover "only" the seasonal storage needs as described above, next to solar and wind power. In that case the 27 EJ by 2050 could be realized with a lower demand on space, which however still equals for palmoil $\sim 7\% \times 27/500 = 0.38\%$ of the surface of the earth. This corresponds to 42% of the current agricultural area (which will generally not be suitable for growing palmoil). In comparison, solar PV with 10% efficiency (which is half of current commercially available Si single junction solar cells), an insolation of 2 kW h m^{-2} day^{-1} (which is less than half of that in Spain), and 60% efficient electrolysis to produce hydrogen would require 1.7×10^5 km^2 ∼3.5% of the agricultural area to collect the 27 EJ. This is a much lower demand on space, even with moderate efficiency solar cells and low insolation values. Also this PV space can be on rooftops or dry, barren land not suitable to grow crops or difficult to reach by road.

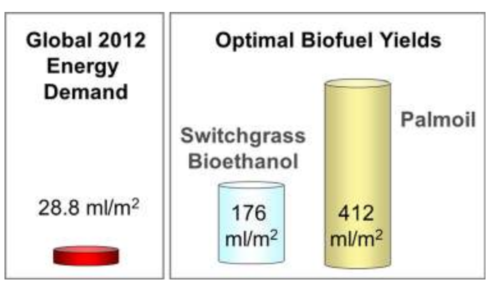

FIG. 7. Illustration comparing the current yearly energy demand with the amounts of experimentally verified yearly optimal biofuel yields. The unit is expressed in ml oil equivalent per square meter of *total earth surface* for the demand and in units of ml of oil equivalent per used square meter for the yields.

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