

Land Availability, Utilization, and Intensification for a Solar Powered Economy

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Abstract

Solar energy, though promising as the energy source for a fossil fuel-deprived future, is a dilute resource and harvesting it requires vast tracts of land. In this study, we develop an extensive process system model for land requirement analysis in each of the 48 contiguous states of the United States for a solar powered economy to address the likely land competition. Land requirement analysis in this study takes into account several issues that are usually ignored. Efficiencies of major energy conversion steps from primary energy to end use are accounted and intermittent solar availability, actual solar farm output and land availability are all considered. In addition, we prefer local photons for local use for consideration of minimizing transmission loss and energy security. Under this preferred scenario, our land requirement analysis shows that 16 of the 48 contiguous states have insufficient available land and that the land competition for energy and food will be intense. Thus, in a solar economy, land use intensification will be required to avoid conflict between our competing land use needs.

Keywords: solar, PV, land, requirement

1. Introduction

Solar energy is our most ubiquitous and promising renewable energy resource that has the potential to meet our future energy demands due to its sustainable availability and abundance (Lewis and Nocera, 2006). Replacing fossil resources with solar power provides an opportunity to eliminate much of the world's pollution, greenhouse gas emissions, and energy security challenges. However, solar energy is a dilute source with power density several orders of magnitude lower than fossil fuels (Smil, 2015). Harnessing solar energy therefore requires vast tracts of land. A number of studies have envisioned a fossil fuel-deprived future powered by solar energy. In most of these previous studies, land availability is not a constraint to the feasibility of a solar powered future. For example, Turner (1999) has estimated that no more than 1 % of the land in the United States, if used for photovoltaics (PV), could provide all the energy needed for the entire country. While these researchers are optimistic about the total solar economy, several recent land requirement analyses have raised the concern in land availability in some densely populated countries. MacKay (2013) has suggested that transition to a total solar economy in Britain would require land area similar to the area of the entire country and that several other high-density, high-consuming countries, such as Japan and Germany, are facing the same challenge. A recent land requirement analysis by Capellán-Pérez et al. (2017) over 40 countries around the world has also pointed out that it could be physically infeasible for many densely populated countries to domestically harness renewable energy to maintain the current energy consumption.

According to these recent land requirement estimations, countries with relatively low population density, such as the US, have sufficient land for solar farms to meet all energy demand.

However, the US is large country where coastal areas are densely packed while other states have relatively less population and energy demand. We would like to see if solar photons could locally fulfil the energy demand. In this work, an extensive systems model for detailed land requirement analysis is developed for each of contiguous 48 states of the US for a full solar economy. In our system model, electricity demand in a solar powered future is first estimated according to current end use energy consumption and energy conversion efficiencies. To take into account the intermittency of solar availability, storage capacity of solar production should be included and various storage methods are deployed. We use the actual PV production data reported (NREL, 2013) to calculate the land area requirement. Furthermore, available land for PV installation is limited; only part of the miscellaneous and urban land could be directly utilized for PV. Considering all the issues stated above, we find out that currently available land is insufficient for many states in the US, which suggests that land competition will be intense in a full solar economy. Novel concepts will be needed to meet food and energy needs in a “Full Earth” maintained by primarily solar energy.

2. System model for land requirement and analysis for a full solar economy

2.1. Methodology for estimating electricity demand in a solar powered future

For the purpose of this study, PV panels are the only devices harnessing solar energy and converting it to electricity supplied to end uses. Therefore, most end use systems are to be electrified for the transition and we need to estimate the total electricity demand (E_{total}^{future}) for electrified end use systems through detailed modeling of each end-use sector (Figure 1). Currently, fossil fuels are either supplied directly to end use sectors or converted to electricity before consumed. In our model, we treat power generation as a separate sector and only direct primary energy consumption is considered for the residential, commercial, industrial and transportation sectors. The systems that might not be feasibly electrified would be powered by synthetic fuels, which are originated from biomass under our assumption. In addition, fossil fuels consumed as feedstocks are also replaced by bio-fuels. The bio-fuel production is also treated as a stand-alone sector.

For the electricity generation, current electricity generated from fossil fuels (EIA, 2016^a) will be replaced by electricity from solar energy (Eq. (1)).

$$E_{electricity}^{future} = \text{Actual electricity generated from fossil fuels} \quad (1)$$

For other end-use sectors, the basis for estimating the electricity demand is to assure that the end-use energy consumptions are the same for current and future scenarios under different energy conversion efficiencies. The calculation paradigm is expressed by Eq. (2)

$$E_i^{future} \eta_i^{future} \eta_{transmission}^{future} = \sum_j E_{i,j}^{current} \eta_{i,j}^{current} \quad (2)$$

where the subscript i refers to the end-use, j refers to the fuel and $E_{i,j}^{current}$ refers to the current primary energy consumption from fossil fuel j for use i . The efficiencies for various end uses and fuels are listed in Table 1.

Table 1: Efficiencies for various end uses and fuels

Sector	End-use (<i>i</i>)	Fuel (<i>j</i>)	$\eta_{i,j}^{current}$	$\eta_{i,j}^{future}$
Residential	Residential	Natural gas, petroleum, coal	65 %	95 %
Commercial	Commercial	Natural gas, petroleum, coal	65 %	95 %
Transportation	Light duty vehicle	Motor gasoline, LPG	14.8 %	75 %
Transportation	Truck	Diesel	20.2 %	75 %
Industrial	Industrial heat	Natural gas	80 %	95 %
Industrial	Industrial heat	Petroleum	80 %	95 %
Industrial	In-house electricity	Natural gas	46 %	-
Industrial	In-house electricity	Petroleum	35 %	-

The primary energy consumption data for each of the end-uses can be acquired from EIA (EIA, 2016^b) and according to the efficiencies listed in Table 1 we can estimate the electricity demand for a future solar economy. Note that the electricity transmission loss is taken to be 4.7 % and therefore a $\eta_{transmission}^{future}$ value of 95.3 % is accounted (EIA, 2016^a).

Now what has been left out is the means of transportation that could not feasibly be electrified and the industrial feedstocks. The fractions of these fossil fuels (e.g. 25.2 % of the natural gas going to industrial sector is for feedstock) are shown in Figure 1. The conversion process from biomass to bio-fuels requires hydrogen to get rid of the oxygen in biomass and the hydrogen is assumed to come from water electrolysis. The electricity required for water electrolysis ($E_{bio-refining}^{future}$) is added to the total solar electricity demand. Therefore, the total electricity demand is calculated by Eq. (3)

$$E_{total}^{future} = E_{electricity}^{future} + E_{bio-refining}^{future} + \sum_{i,j} E_{i,j}^{future} \quad (3)$$

where i, j are listed in Table 1.

2.2. Intermittency of solar energy, PV output and land availability

One of the essential challenges of solar energy utilization is the intermittency of solar availability. In the US, the average solar availability is only 4.8 hours per day, which means that all the solar electricity demand must be produced in 1/5 time of a day (Lewis and Nocera, 2006). The electricity produced in the solar available time period needs to be stored. Currently, the battery storage efficiency varies in the range of 75 - 94 % (Gençer and Agrawal, 2016) and carbon storage cycle has an efficiency of 55 - 58 % (Al-Musleh et al., 2014). We adopt a mixed energy storage method and the overall system storage efficiency is taken to be 65 %. Considering the intermittency and the storage efficiency, the corrected total electricity for a solar economy can be calculated by Eq. (4) where $f_{solar\ available}$ refers to the fraction of solar available time in a 24-hour day, which is 20 % here.

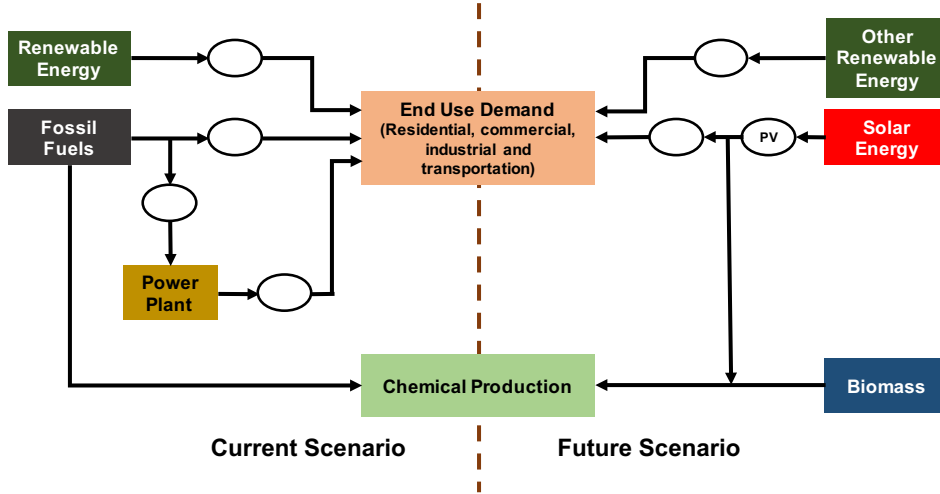


Figure 1: The energy supply infrastructure of current and future scenarios. The current end use demand will be maintained by solar energy in the future. Ovals in the figure indicate the energy conversion efficiency.

$$E_{corrected}^{future} = E_{total}^{future} f_{solar\ available} + E_{total}^{future} (1 - f_{solar\ available}) / \eta_{storage} \quad (4)$$

A reasonable PV output number is crucial for our land requirement analysis. Although the maximum solar cell efficiency reported to date can be up to 46 % (NREL, 2017), the actual PV power output from PV parks is generally much lower. Instead of estimating PV power output by looking at the solar flux and PV efficiency as in most of the previous studies, we use actual production data of existing PV parks. An average power production of ~ 7 W/m² is reported for PV installations that are greater than 1 MW in size (Ong, 2013) and we take this number for our land requirement analysis. In addition, we average the total electricity demand over the total time of a year to obtain the total power output requirement (p^{future}) for a solar economy (Eq. (5)).

$$p^{future} = \frac{E_{corrected}^{future}}{\text{Total time of a year}} \quad (5)$$

Then we can calculate the land requirement for each of the contiguous states as we know the total power output requirement and power output density for PV parks ((Eq. (6)).

$$\text{Land area} = \frac{p^{future}}{\text{power output density}} \quad (6)$$

3. Miscellaneous and urban land are insufficient

Land area available for PV installation is only limited to certain types of land. Agriculture land (croplands, grassland pastures and ranges) cannot be used for PV installation as food production will be harmed by PV panels. Forest-use land and special-use land (national and state parks, etc.) are also unsuitable for PV for the consideration ecosystem protection. Agriculture land, forest-use land and special-use land account for 93.2 % of the total land of the US. Only part of urban-use land can directly be used for rooftop PV and other miscellaneous land (marshes, deserts and

other barren land generally of low value for agricultural purposes) is currently available for PV parks.

If we compare the land area requirement estimated in Section 2 and the area of miscellaneous and urban land for each of the contiguous 48 states in the US (Figure 2), we can see that there are 16 states that need more than 50 % of the miscellaneous and urban area. For Wyoming, West Virginia and Texas, even more than 100 % of the miscellaneous and urban land are required for PV. What we have to note is that 50 % is a rather high utilization ratio, especially for urban area. Existing studies have shown that only a small percentage of urbanized area could be covered by solar panels, generally no more than 10 %, with acceptable solar conversion efficiency (Capellán-Pérez et al., 2017). Therefore, for the highly urbanized coastal areas, such as California and New Jersey, the land challenge could be more severe. Clearly, a significantly large number of states will not be able to meet their need locally and will have to import energy from other parts of the country. Alternatively, options to use other land areas such as agricultural land should be explored. This could be challenging as current practice of using photovoltaics on farmland is known to hurt food production or alter crops that can be grown (Armstrong et al., 2016).

Moreover, our energy demand estimation is based on the energy consumption data for the year of 2014. With population growth and economic development, the energy demand could be higher in the future, which would require more land dedicated for power production. In addition, population growth would require more land for human activities. Therefore, the land competition will be more challenging in a full earth. To resolve this land issue for the realization of solar economy, additional land apart from urban and miscellaneous land will be locally required.

4. Conclusions

To transition to a full solar economy, an extensive systems model is developed accounting for harnessing solar energy as electricity, its storage, transportation and use. The model is then used for detailed land requirement analysis in each of the contiguous 48 states of the United States to examine the possible land usage for energy. Results show that for a future solar economy, 16 states are likely to require more than 50 % of the miscellaneous and urban land for solar power generation. Our results are in sharp contrast to the common understanding that only small land areas will be needed in a future solar economy to satisfy entire energy need. These results show a need for innovation in land use intensification including the possibility of using farmland while causing no reduction in food production.

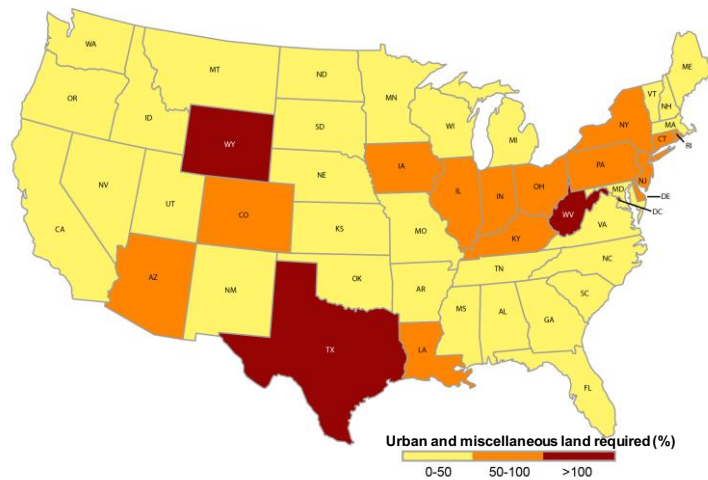


Figure 2: The percentage of miscellaneous and urban land required for PV

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