Energy Policy 123 (2018) 83–91

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S.

John van Zalk[a], Paul Behrens[a,b,*]

[a] *Leiden University College, Leiden University, P.O. Box 13228, 2501 EE The Hague, the Netherlands*
[b] *Institute of Environmental Sciences, Leiden University, P.O. Box 9518, 2300 RA Leiden, the Netherlands*

ARTICLE INFO

Keywords:
Energy transition
Spatial impact
Power density
Energy systems
Land
Energy models

ABSTRACT

Energy systems are undergoing a significant shift to renewable energy (RE). To date, the surface area required for RE systems is greater than that for non-RE systems, exacerbating existing environmental policy challenges, from increasing land competition, to visual impacts. A suitable metric for comparing the extent of systems is the power density of electricity production, that is, the electrical power produced per horizontal m^2 of surface area. This study systematically reviews power densities for 9 energy-types (wind, solar etc.) and multiple sub-types (e.g., for solar power: PV, solar thermal) in the United States. Median, mean, and uncertainty estimates are provided for 177 different densities from the literature. Non-renewable power densities are found to be three orders of magnitude larger than renewable densities. Natural gas and solar energy yield the highest median density per non-RE, and RE system respectively. Solar energy was the only system to experience a significant, positive relationship in power density over time. We apply these density estimates to NREL scenarios of future energy systems for state-specific assessments, and find that the largest growth in land use is in the southern United States.

1. Introduction

Renewable energy (RE) has generally lower power densities than other non-renewable sources Smil, 2010). That is, RE typically requires more surface area to produce an equivalent amount of power as non-RE system. Given the two-fold importance of land competition and visual impacts, the clean energy transition has led to increasing interest in the spatial impact of energy systems (Bridge et al., 2013; Fouquet, 2016). Smil (2016, 2010) and Mackay (2009a, b), find that future RE systems will cover a significant percentage of available land in the United States and United Kingdom respectively. Smil (2016), highlights that renewables produce energy at a small fraction of current power densities in use in urban areas and industry. Thus, he sees growth in the footprint of the energy sector as inevitable, having to harness renewable flows over extensive areas and in populous centres. In one exploration of a scenario balancing many national concerns, Mackay finds that the production of biofuels would require the majority of available, arable land in the UK (MacKay, 2008). However, other researchers suggest that while the area of energy systems may increase, the growth in land-use by the energy sector would be minor, since RE would be predominantly placed atop existing infrastructure and offshore (most generally rooftop solar, De Boer et al., 2011).

Energy systems modelling can benefit from reliable power density estimates (Brehm et al., 2016; Chiabrando et al., 2009; Delucchi and Jacobson, 2011; Denholm et al., 2000; Honeyman, 2015; Mackay, 2009a, b; NREL, 2012; Sands et al., 2014). Several studies have included spatial implications in long-term market potential, and maximum, production values (Brehm, et al., 2016; Feldman et al., 2015). Studies by Jacobson and Delucchi use power densities to estimate several outcomes in future regional and national energy systems (Delucchi and Jacobson, 2011; Jacobson and Delucchi, 2011). These studies include investigations for meeting energy demands with hydroelectricity, wind, and solar for the world (Jacobson and Delucchi, 2011), and road maps for individual US states (Jacobson et al., 2015). In contrast to other work (MacKay, 2008; Smil, 2010), Jacobson and Delucchi find areas that renewable energy infrastructure would occupy a small fraction of total land available. This has been recently challenged in other works (Clack et al., 2017).

The National Renewable Energy Laboratory (NREL) incorporates power densities to produce estimates of achievable energy generation of each established technology in the U.S. given system performance, topographic limitations, environmental, and land-use constraints (Lopez et al., 2012). For rooftop studies, NREL estimated the percentage of households and buildings that could host PV systems in the United

---

[*] Corresponding author at: Leiden University College, Leiden University, P.O. Box 13228, 2501 EE The Hague, the Netherlands.
E-mail address: p.a.behrens@luc.leidenuniv.nl (P. Behrens).

https://doi.org/10.1016/j.enpol.2018.08.023
Received 4 August 2017; Received in revised form 8 August 2018; Accepted 10 August 2018

States (Feldman et al., 2015). Gagnon et al. (2016) went further, estimating hosting potential by building size.

Improved understanding of power densities may help examine trade-offs between different land-uses and their social implications. For example Bridge et al. (2013) discuss which types of land will be used more often as renewables gain market penetration, including uplands (wind), narrow sea passages (hydro), and rural environments. Chiabrando et al. (2009) used theoretical power density values in a risk assessment of human vision loss due to glare from a PV system in Italy.

Even though the studies mentioned above use estimates of the spatial extent of power generation, few have compared energy types in a single, standard unit. Layton (2008) determined power densities in J/m^3 – giving concentration information, but not surface area requirements. Perhaps the most inclusive estimates have been produced from life-cycle analyses (Fthenakis and Kim, 2010; Gagnon et al., 2002). These estimates compare systems in terms of m^2/Wh. However, they do not incorporate a capacity factor, which for renewables is a serious consideration (given the availability of renewable flows). A more general comparison of surface areas is based on the unit of power – the average electrical power actually transmitted to the grid over some time period (usually a year) in W_e/m^2. Smil (2010) provided high and low estimates for horizontal power density (power density henceforth) by examining the limits of generation arrangements. For example, comparing surface and underground mines for different forms of coal generation.

However, research is lacking on average power density values for energy types and sub-types. It is also not clear whether industries in general trend towards Smil's high or low predictions. Uncertainty estimates are also lacking, precluding the ability of providing further sensitivity estimates in energy system modelling. This paper addresses this knowledge gap by calculating power densities for nine established technologies in the United States including: natural gas, nuclear, oil, coal, solar, wind, geothermal, hydro, and biomass. Within these energy types, the power densities of sub-types are also presented (i.e. switchgrass, palm oil etc.). A literature review is performed, and 177 electric power densities in W_e/m^2 from 54 publications are evaluated. Note that although this research focuses on a particular country, the work can be used as an estimate for nations with similar technological and resource availabilities. To investigate whether power densities have changed appreciably over time, implying improving technical implementation, a statistical analysis of developments is conducted. Finally, the power density estimates are applied in an example analysis of two NREL scenarios for the power sector through to 2050. NREL scenarios are chosen since they include national, sub-national, and state-by-state changes in land-use for the power system. To our knowledge this is the first work examining power densities across the literature for different energy types and sub-types.

The article proceeds as follows: Section 3 presents the methods and data used, including the search terms and inclusion criteria; Section 4 presents the results of the meta-analysis and presents visualizations of the land requirements for the electricity sector over time; Section 5 discusses the findings in the context of land and energy policy; Section 5 offers final remarks.

2. Methods and data

This study follows PRISMA guidelines for transparent meta-analysis reporting, which are current as of May 2017 (Moher et al., 2015). The databases searched included: Web of Science, Leiden University Catalogue, ScienceDirect, NREL Publications, and GreenFILE. Theses searches were supplemented using snowball sampling. Works containing the phrase ‘power densities’ related to other fields such as transportation, medicine, fuel cells, communication devices, buildings, magnetic fields, food chains, etc., were excluded using appropriate search terms. See Appendix Table 1 and Appendix Table 2 for a full list of search terms (including result frequencies) and citations respectively. The inclusion criteria were that: (1) all publications be in English; (2) all publications except government reports were peer-reviewed; (3) publications giving location-dependent power densities are specific to energy sources or technologies in the U.S.; (4) power densities are for electric power production as opposed to heat generation or liquid biofuel production; and, (5) the publication presents an average or range of power densities rather than one for a specific, individual power plant. This final criterion is important as power densities for specific plants are non-representative since they report experiments rather than developed technologies. Note that there is no time-exclusion criterion in this analysis, because a goal of this study is to examine the change in power densities over time. The earliest paper to feature in this analysis is from 1974. A flow diagram of available studies through the selection process is shown in Fig. 1.

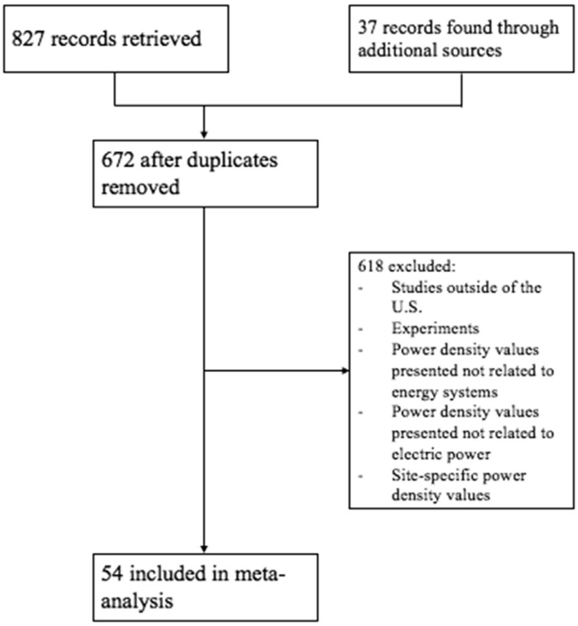

Fig. 1. Flow chart of the selection of eligible studies.

Once the articles were screened, power densities and other details were extracted. Parameters extracted include: publication date, type of energy (e.g. biomass), sub-type within energy type (e.g. switchgrass), power/energy density, the unit reported (e.g. MMBTU), and the type of study (see Appendix Table 3). Additionally, the methods used in each publication were evaluated to determine whether the value accounted for the total footprint (i.e. surface area use in additional infrastructure), efficiency, and/or capacity factor. Finally, the articles were reviewed for citations to other relevant articles in a snowball sampling approach. For articles reporting wind power densities for multiple different wind speeds, the value of the U.S. average (5.5–7.0 m/s) was taken (Archer and Jacobson, 2005; U.S. Environmental Protection Agency, 2013a).

The majority of studies reported power density values which do not represent total footprints, nor did they include efficiencies or capacity factors. These raw power densities were converted to the power density of produced electric power PD_e in W_e/m^2,

$$PD_e = PD \times \eta_{eff} \times CF \times infrastructure \tag{1}$$

which incorporates the power density of the resource before conversion PD (in W/m^2), the unitless efficiency of the energy converter η_{eff}, the unitless capacity factor CF, and the unitless infrastructure requirement ratio, which represents the additional surface area required for mines, roads, foundation pads etc. as a ratio of direct surface-area of resource to total surface-area including infrastructure for each energy type. Efficiencies, capacity factor, and infrastructure were taken from the literature and are given in Appendix Table 4, 6, and 9 respectively. For