Land-use intensity of electricity production and tomorrow's energy landscape

Jessica Lovering[a]*, Marian Swain[a], Linus Blomqvist[a], Rebecca R. Hernandez[b,c,d,e]

Corresponding Author

Jessica Lovering
lovering@umich.edu

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[a] Breakthrough Institute, 436 14th St. Suite 820, Oakland, CA 94612, USA

[b] Energy and Resources Group, 310 Barrows Hall, University of California, Berkeley, California 94720, USA

[c] Climate and Carbon Sciences Program, Earth Sciences Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Rd, Berkeley, California 94720, USA

[d] Department of Land, Air, & Water Resources, University of California Davis, One Shields Ave., Davis, CA 95616, USA

[e] Wild Energy Initiative, John Muir Institute of the Environment, University of California, Davis, One Shields Ave., Davis, CA 95616, USA

* *Corresponding author*

Abstract

Humanity's land footprint is predominantly characterized by agriculture (30-38%), built-up areas (0.5-2.6%), and planted forests (0.9-1.6%), while land used for energy systems has a comparatively insignificant share (0.4%). However, future energy scenarios that focus on deep reductions in greenhouse gas emissions could dramatically alter the landscape, particularly given the projected doubling of global energy consumption and widespread electrification of transportation and industry. Here we calculate land-use intensity of energy (LUIE) for real-world sites across all major sources of electricity, integrating data from published literature, databases, and original data collection. We find a range of LUIE that span five orders of magnitude, from nuclear with 7.1 ha/TWh/y to dedicated biomass at 58,000 ha/TWh/y. By applying these LUIE results to the future electricity portfolios of ten energy scenarios, we conclude that there is potential for a significant increase in land-use for electricity production, and we discuss the main drivers and uncertainties.

Providing energy for a population of over 7 billion and nearing 10 billion by mid-century has many impacts on public health and the environment beyond just carbon emissions. These impacts include water use, materials consumption, local particulate pollution, and land use. The land footprint of energy production can displace natural ecosystems, lead to land degradation, and compete with food production, urban development, and other land uses. For example, a recent analysis showed that energy sprawl is now the largest driver of land-use change in the United States[1].

This land footprint may become an even larger driver of environmental impacts in the coming decades, if energy demand rises rapidly in developing countries and countries shift their mix of energy sources to meet decarbonization targets[2], potentially towards more land-intensive energy sources. As a result, energy development may be equal to or exceed the area projected for agriculture and urban expansion as a major driver of land-use change globally, but such projections are lacking for energy.

Specifically, the land footprint of energy is seldom considered in regional and global assessments of decarbonization pathways, land-use change, and biodiversity threats, with the occasional exception of particularly land-intensive sources like bioenergy[3–5 6–9]. Hence, there is a need to consider land use as a key factor in energy systems planning, along with other environmental impacts, public health, greenhouse gas emissions, affordability, and energy security.

There only exist a limited set of existing studies that assess Land-Use Intensity of Energy (LUIE) across all major electricity sources and all have methodological weaknesses. Previous studies either calculate LUIE based on a single installation[10], a small number of non-randomly selected facilities[11–13], or use modeled electricity generation data, which may not reflect actual performance[1]. Several studies that provide LUIE results for single energy technologies or technology groups. Data from these studies are incorporated in this paper[14–17].

In this study, we collected and calculated the land-use intensity (measured as ha/TWh/year) for real-world electricity generation – not hypothetical or modeled electricity generation – across all major sources of electricity and a broad geographic distribution. We focus on the land footprint of electricity only, as most future energy scenarios predict large growth in electricity consumption as transportation and industry electrify to reduce emissions, and electricity production has the broadest range of technologies with diverse land use impacts[18,19]. Our data set covers 66 countries and 45 US states. Data are collected from 17 published studies as well as public records, datasets, and original geospatial analysis (see Supplementary Information for full details). We cover coal, natural gas, nuclear, wind, solar photovoltaic (PV), concentrated solar power (CSP), geothermal, hydroelectric, and biomass (including electricity from dedicated biomass feedstock production, hereafter called “dedicated biomass”; and electricity from waste and residue biomass, hereafter called “residue biomass”).

We then apply our LUIE results to ten prominent scenarios for future energy supply. These scenarios vary greatly in their mix of renewables, fossil fuels, and nuclear energy, but all had large increases in global electricity generation. As a whole, our study facilitates a quantitative and comparative understanding of the balance between energy, land use, and climate change mitigation and the implications of a build-out of low-carbon electricity sources on global land use.

Calculating Land Use Intensity of Electricity Sources

Our LUIE calculations include land occupied by the electricity-producing facility (called "direct area") and, if applicable, the land needed to source power plant fuel (called "indirect area"). For wind and natural gas, we offer two definitions of occupied land: "footprint" and "spacing" area. Footprint land is covered by physical components of a power plant, while spacing is the land in between physical components in an electricity generation or fuel extraction site. For wind, footprint area measures only the area covered by turbine pads and access roads, while spacing area measures the entire area within the boundaries of the wind farm. For natural gas, footprint area for the indirect land use measures only the area covered by well pads, access roads, and pipelines, while spacing area includes the entire area inside the perimeter of a natural gas production field.

We find that median LUIE varies by four orders of magnitude across the electricity sources considered in this study (Figure 1, Table 1). Nuclear had the lowest LUIE at 7.1 ha/TWh/year, and dedicated biomass the highest at 58,000 ha/TWh/year.

Indirect land use for combustion-based electricity – land used for fuel sourcing for coal, natural gas, and biomass - is a larger share of LUIE than direct land use. Indirect land use comprises over 90% of total land use for natural gas generation, approximately 55% for coal generation, and close to 100% for dedicated biomass (see Supplementary Information for more details on data sources). The opposite is true for nuclear power, where indirect land use for uranium mining is only 10% of total LUIE and the majority of land impacts were from the power plant itself. When including accident exclusion zones in the total LUIE for nuclear, indirect land use drops to 6% of total. Although our calculations do not include upstream land impacts from manufacturing of materials, other studies of renewable energy technologies find upstream land demands to be negligible, less than 1% of total land use[11].

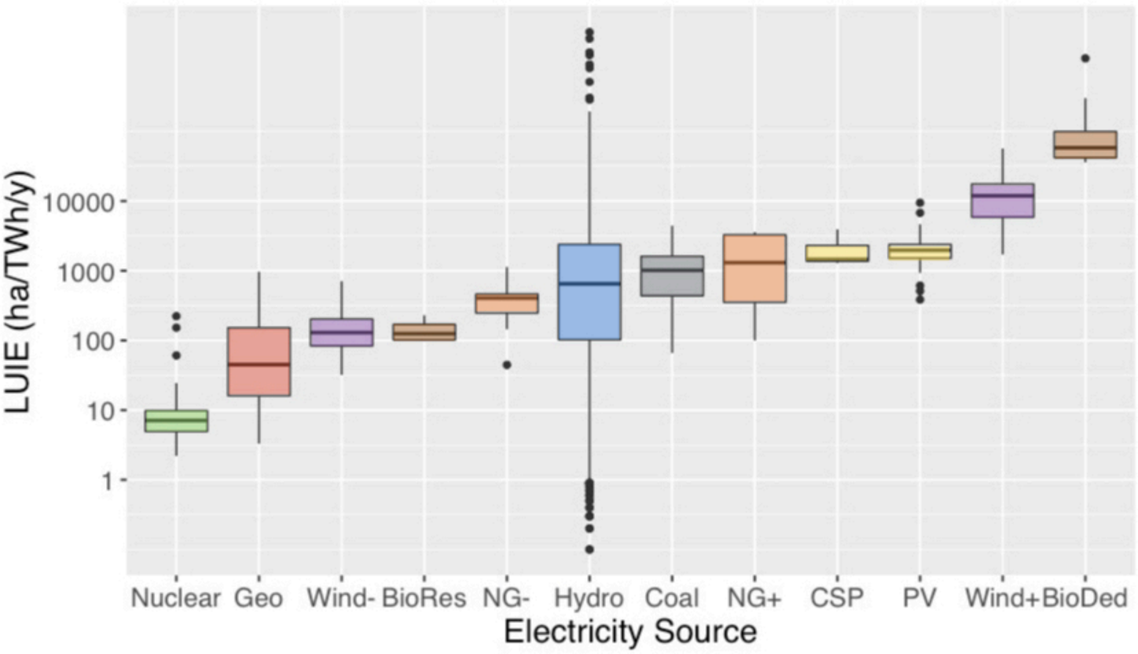

Figure 1. Land use intensity of electricity (LUIE: ha/TWh/y), shown on log scale. Boxes represent the inter-quartile range with the median as the middle bar. Whiskers extend to the highest or lowest data point that is within 1.5 times the inter-quartile range; points outside this range represent outliers. Electricity sources: nuclear energy (Nuclear), geothermal energy (Geo), wind energy with footprint only, (Wind-), natural gas footprint only (NG-) and including spacing (NG+), hydroelectric power for single purpose dams (Hydro), coal (Coal), concentrating solar power (CSP), ground-mounted photovoltaic solar energy (PV), wind energy with footprint (Wind-) and spacing (Wind+), and residual biomass (BioRes) and dedicated biomass (BioDed).

To test for statistical differences in LUIE across different sources, we conducted an ANOVA analysis with Tukey's pairwise comparisons on the natural logarithm of the means of the different sources (Table 1). The ANOVA model uses pooled variance and has an R^2 of 90.46%. Hydroelectric energy was excluded due to its large variance, which would compromise all the pairwise comparisons since it increases the pooled variance.

According to this analysis, dedicated biomass, wind (footprint and spacing), geothermal, and nuclear were significantly different from every other source. Ground-mounted PV, solar CSP, and natural gas (spacing) were not significantly different from each other; the same was true for solar CSP, natural gas (spacing), and coal. Natural gas (spacing) was not significantly different from natural gas (footprint). Hydroelectric has a large variance, even after we narrowed our analysis to dams that are only used for power generation, excluding dams with secondary purposes for irrigation, flood control, and drinking water supply.

Table 1. Land use intensity of electricity (LUIE) showing total direct and indirect land use (ha/TWh/y). We show median, mean, and interquartile range (IQR) for the LUIE, along with the number (n) of observations for each energy source. We performed an ANOVA analysis with Tukey's pairwise comparisons on the $\log_{10}$ of the means of LUIE for different sources, which is represented by different letters. Sources that share a letter are not statistically different. Hydroelectric was excluded from the ANOVA analysis because its variance was too large.

	ANOVA Tukey's Pairwise	**LUIE Median**	**LUIE IQR**	**LUIE Mean**	**LUIE Standard Error**	**LUIE n**
Nuclear	A	7.1	4.8	15	4.4	59
Geothermal	B	45	150	140	46	26
Wind (footprint)	B	130	120	170	18	57
Residue biomass	B C	130	71	150	31	4
Natural gas (footprint)	C	410	210	410	58	17
Hydroelectric (single purpose dams)	---	650	2,300	15,000	4,300	952
Coal	C D	1,000	1,200	1,100	170	30
Solar CSP	D E	1,500	1,100	2,000	410	7
Natural gas (spacing)	C D E	1,900	2,800	1,900	890	4
Ground-mounted PV	E	2,000	860	2,100	120	94
Wind (spacing)	F	12,000	12,000	15,000	1,700	57
Dedicated biomass	G	58,000	59,000	160,000	77,000	14

Comparing LUIE and Life-Cycle GHG Emissions

Land-use intensity and GHG emissions are both important metrics for assessing the environmental impacts of energy production. We identify several electricity-generating technologies that minimize both land use (from our LUIE results) and GHG emissions (median results for the entire electricity life-cycle from IPCC)[20], including integrated PV (e.g., on rooftops), nuclear, wind (footprint only), and geothermal (Figure 2). The large variance of hydroelectric, biomass, and geothermal reflect the dependence of these sources on local conditions. A dam in a steep mountain valley generates large amounts of electricity on very little land, compared with a dam in a shallow basin. Similarly, the type of land flooded to create the reservoir, or the type of biomass feedstock used can lead the large difference in lifecycle GHG emissions.

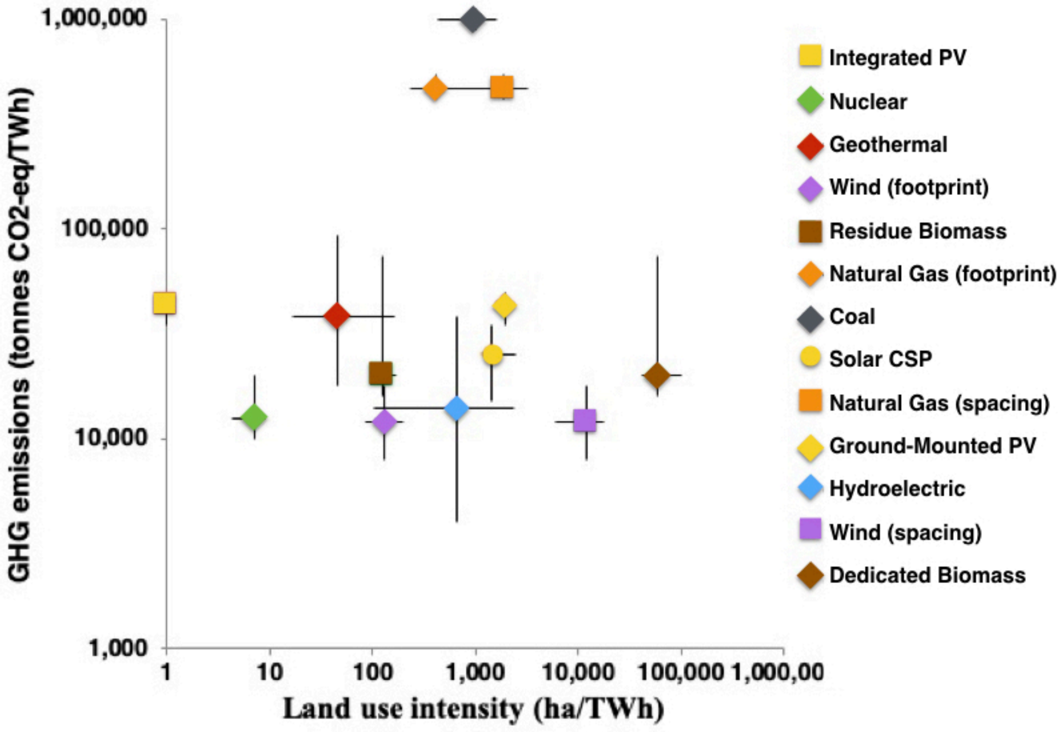

Figure 2. Relationship between the land use intensity of electricity (ha/TWh/y) and lifecycle GHG emissions (metric tons CO^{2}-eq/TWh) on a log scale. Error bars represent interquartile range. GHG emissions source data: IPCC Fifth Assessment, Working Group III[20].

Future Energy Scenarios Imply Significant Land Use Change

We applied our mean LUIE results to the electricity mix of future scenarios for the global power sector, as well as to today's global electricity mix[21], to determine the current and projected land requirements for future global electricity roadmaps (Figure 3). Our LUIE results suggest that current total global land use for electricity production is approximately 72 (±1.7) Mha, with 80% of that land used for hydroelectric dams.

We assessed ten global decarbonization pathways from six different organizations and studies: the 2, 4, and 6 degree Celsius scenarios from the International Energy Agency's *Energy Technology Perspectives* (hereafter "IEA")[22], Greenpeace's *Energy [R]evolution* ("GP")[23], World Wildlife Fund's *Energy Report* ("WWF")[24], three scenarios from the *Global Energy Assessment* ("GEA")[9], Jacobson & Delucchi ("JD")[25], and Barry Brook ("Brook")[26]. Real-world land requirements vary by region and the dynamics of land-use change are highly context-dependent. These projections are not intended as forecasts, but rather as estimates of the scale of land use that would be needed for electricity production in hypothetical decarbonized electricity portfolios.

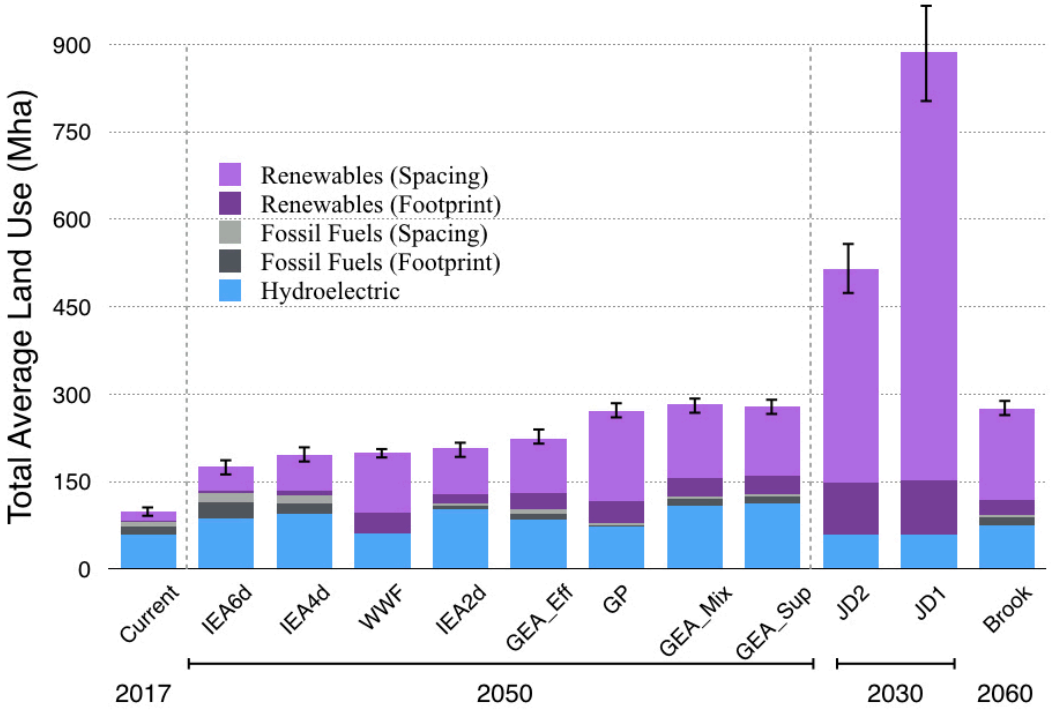

Figure 3. Land area (Mha) for future electricity generation scenarios, broken down by source of land use: hydroelectric, fossil fuels, non-hydro renewables, and spacing from wind and natural gas. Land use for biomass electricity is included in non-hydro renewables, but we assume all biomass comes from residue or waste for these calculations, thus representing a lower bound. JD1 refers to the Jacobson & Delucchi scenario assuming all wind is onshore, and JD2 assumes 50% of wind is onshore and 50% is offshore. Total land required to generate electricity in each future decarbonization scenario is shown with standard errors. GEA_Sup, GEA_Eff, and GEA_Mix are the GEA Supply, Efficiency, and Mixed scenarios respectively. Electricity generation data for the current mix (2017) comes from the BP Statistical Review.

Our analysis suggests the possibility of a significant expansion of the land footprint for electricity in the coming decades, ranging from an additional 30-80 Mha for physical footprint to and additional 80-800 Mha when spacing is included. The scenario with the lowest total land-use was the IEA 6 Degree scenario, which is a business-as-usual scenario that includes a large share of fossil fuels. The WWF and Greenpeace scenarios also had low total land use, but this was in part due to their lower overall projected electricity consumption, as well as their limited reliance on large hydroelectric. Brook had lower land-use despite higher overall electricity consumption, primarily due to their reliance on nuclear power, which has the lowest LUIE. The Jacobson scenarios had the highest land use both because they were converting all global energy use to electricity, and they also rely extensively on wind and solar.

The projected expansion of land-use across these scenarios is a similar order of magnitude to the value projected for global urban expansion (60-241 Mha)[27], and when spacing is included this may exceed forecasted cropland expansion (average 160-320 Mha of various projections)[5]. If biomass was to come from dedicated feedstocks, the additional land required would be between 80 and 700 Mha across these scenarios. For comparison, Jacobson et al. (2017) estimated that the land required for a 100% renewable system would be lower than our calculation (35 Mha or 177 Mha with spacing), but their land-use figures represent hypothetical electricity generation, which tends to be lower than realized generation from our surveys[19]. Trainor et al (2016) calculated additional land use from EIA scenarios in the US and found land use could grow by 18-24 Mha by 2040, but this is for all energy production in the US (not just electricity)[1].

Sourcing of Biomass Carries Great Uncertainty

Future biomass demand will likely be met by a mixture of waste or residues and dedicated feedstocks. However, the average land-use intensity of residue and dedicated biomass differs by four orders of magnitude. To represent an upper boundary on our results, we could assume all biomass comes from dedicated feedstock production. This upper bound estimate results in biomass comprising over 99% of the total land use in future energy scenarios (unless the scenario excludes biomass). The GP, WWF, and GEA energy scenarios reviewed here specify that the biomass in their scenarios should come only from forestry and agricultural wastes and residues, rather than dedicated production. The level of biomass required in those scenarios is within the range of global technical potential[28], but estimates of global technical potential do not reflect economic or geographic constraints on biomass residue recovery (see Supplementary Information). There is also evidence at the regional level that residues alone are unlikely to meet bioenergy demand, which could result in increased logging and displacement of other wood products[29]. To take a lower bound on biomass, we could assume all feedstock comes from waste or residue. Then biomass constitutes only about 1% of total land use in future energy scenarios.

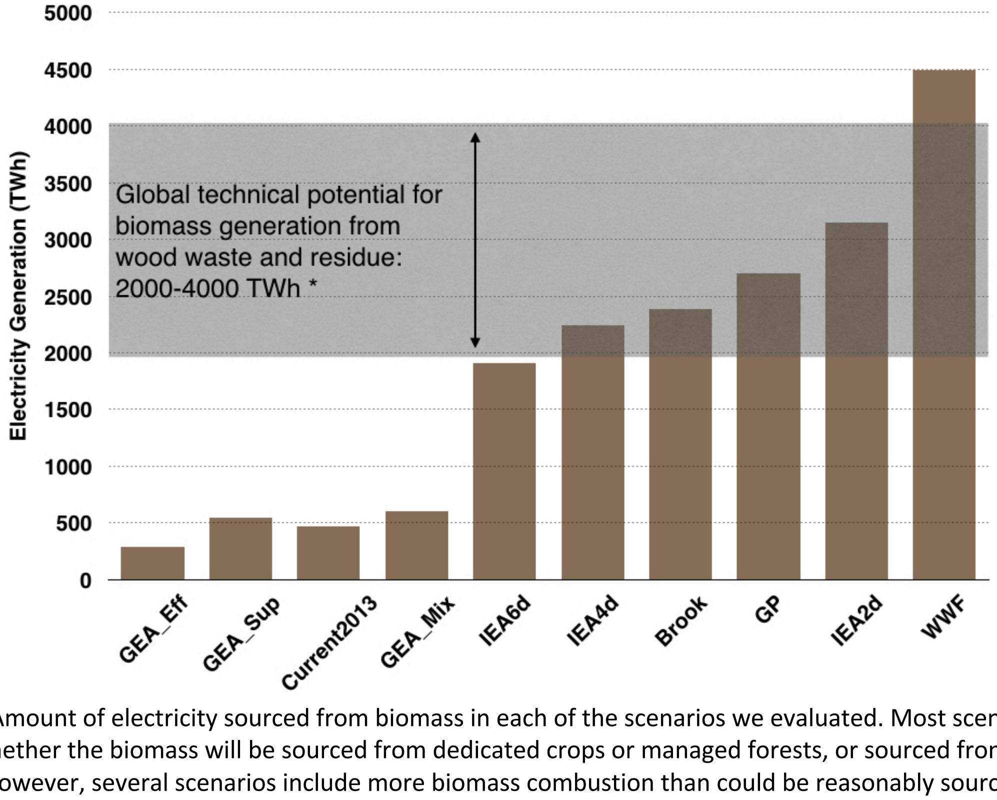

Figure 4. Amount of electricity sourced from biomass in each of the scenarios we evaluated. Most scenarios do not specify whether the biomass will be sourced from dedicated crops or managed forests, or sourced from waste and residue. However, several scenarios include more biomass combustion than could be reasonably sourced from waste and residues, assuming all waste and residue produced globally could be economically collected. *Global technical potential for biomass production comes from Searchinger and Heimlich (2015).

Potential to Co-Site Reduces Land Intensity

Renewable energy sources like ground-mounted PV, CSP, and wind feature prominently in many decarbonization scenarios, but since they can have higher land use intensity than fossil fuels, large-scale deployment of these technologies could considerably increase energy sprawl and loss of natural habitat. The types of landscapes impacted will vary by energy source, and while there are several opportunities for mitigating the land requirement of low-carbon electricity systems, there is also evidence that renewable energy development to-date has often occurred on previously undeveloped land[30,31].

Some power technologies can produce electricity without requiring additional land. Solar PV can be placed on pre-existing rooftops or over parking lots[32], wind turbines can be built on agricultural land[33], biomass feedstock can be sourced from residues and waste materials[28], and nuclear power plants can be built on transportable ships or trucks[34]. Dams that were originally constructed for water supply, irrigation, or flood control can have hydroelectric capabilities installed at a later date[35]. However, there are limitations on scaling these non-additional sources. Integrated PV faces barriers owing to economic, policy, and technological constraints. A recent estimate put the technical potential of rooftop-mounted solar PV in the United States at 1,400 TWh/y – about 38% of current US electricity demand[36]. As a technical potential, this estimate is higher than the economic or market potential for the technology. Currently, only about one-third of US solar capacity is in distributed rooftop installations, while the rest is from ground-mounted, utility-scale power plants[37], of which, in the case of California, the plurality are sited in natural habitats like scrublands and shrublands[30].

Some of the scenarios imply a need for vast spacing areas, with the majority of spacing area allocated to wind (see Supplementary Table S1). Wind can be co-located with agricultural land and thus reduce additional land impacts; Denholm et al. (2009) estimate that half of US wind is co-sited with cropland or pasture[31]. However, onshore wind at the scale employed in the JD scenario would require approximately 350 Mha of spacing area, an area greater than 20% of current global cropland.

Additionally, areas with good wind resources and proximity to end users do not always overlap with existing agricultural area, sometimes requiring wind energy development on previously undeveloped land, as was recently found to be the case in California[38]. Finally, energy infrastructure can create habitat fragmentation and disturbance that adversely affects wildlife behavior beyond the boundary of the physical footprint[6,39,40].

Discussion

By surveying a broader range of real-world electricity generation sites, we demonstrate the large variability of land-use intensity within each generation technology. Our results suggest that production of electricity to meet decarbonization goals could become a significant new driver of land-use and land-cover change with implications for habitat and biodiversity loss, food security, and other environmental and social priorities. An expanding footprint is not inevitable: the LUIE for integrated PV, nuclear, the footprint of wind, and geothermal are each less than coal or natural gas, which together, currently generate more than 60% of the world's electricity[22].

Impacts of energy development can be mitigated through strategic local-scale approaches that consider proximate impacts within and near development boundaries and landscape-level approaches that target more systemic, cumulative impacts of entire energy systems[41,42]. Decision-support tools can integrate multiple criteria, leading to reductions in various types of environmental and social impacts while optimizing generation with respect to the cultural and economic interests of stakeholders[43]. Examples of such approaches already exist for several regions and sources, including hydroelectricity and solar energy[32,38,44,45]. However, even with better siting, the larger the aggregate footprint of energy, the more likely environmental impacts are to grow[12]. This underscores the long-term environmental benefits of electricity sources that have both low land and carbon footprints, and the importance of using LUIE as a metric alongside other factors like GHG emissions, cost, and reliability in planning and governance of energy development.

Methods

Our LUIE dataset is compiled from nine peer-reviewed studies, eight published reports from government agencies and national labs, and eight databases. To provide LUIE results representative of the current state of each energy technology, we required that data sources represent existing, operational energy facilities and real world, rather than modeled, electricity generation data. As we only focused on electricity generation, we excluded liquid biofuels used in transportation and traditional biomass used directly for heating and lighting.

We drew on peer-reviewed literature to aggregate data for coal, natural gas, and biomass LUIE. For geothermal, hydroelectric, and solar, we combined data from past studies and publicly available datasets. For wind and nuclear, we calculated area requirements using Google Earth Pro and collected electricity generation data from US Energy Information Administration (EIA) databases. Where possible, we obtained globally representative samples of energy facilities, but due to limitations on electricity generation data for individual power plants, data for the following energy sources include only facilities in the United States: nuclear, wind, ground-mounted PV, and solar CSP. For solar PV and wind, we expect LUIE to be similar across countries as the technology is produced by a small number of international suppliers and depends mostly on solar insolation. For nuclear power, we expect the LUIE based on US plants to be an upper bound, as most other countries with large nuclear fleets have larger numbers of reactors at each site, leading to economies of scale in terms of occupied land.

Our LUIE calculations do not include land that is occupied by the upstream manufacturing of electricity generating facilities (e.g., the land required to mine materials for solar panel or wind turbine production, of the materials that go into nuclear or coal power plants). We also exclude land required for electricity transmission infrastructure (e.g., high voltage transmission corridors), offshore area impacts (for wind farms and natural gas drilling), and underground impacts (for geothermal, natural gas, and underground coal mining).

The formula to measure direct LUIE (Equation 1), involves dividing the land occupied by an electricity-producing facility by the energy it produces over a year[12,14,46–49]. For most combustion-based generation - except nuclear - the power plant is only a small proportion of the land occupied to produce energy, with fuel production taking up a much larger amount of land. We call the area for fuel production indirect land use (Equation 2). This indirect land use applies to coal, natural gas, dedicated biomass, and nuclear, which require externally-sourced fuel. Total LUIE (Equation 3) is the sum of direct and indirect LUIE. Where data for a single facility was incomplete, for example only direct LUIE was provided, it was combined with the average indirect LUIE result from other sources to calculate total LUIE.

$$LUIE_{direct} = \frac{A_{direct}}{Energy} \left[\frac{ha * y}{TWh}\right]$$

Equation 1: Direct land use intensity

$$LUIE_{indirect} = \frac{A_{indirect}}{Energy} \left[\frac{ha * y}{TWh}\right]$$

Equation 2: Indirect land use intensity
(applicable energy systems: coal, natural gas,
biomass, nuclear)

$$LUIE_{total} = \frac{A_{direct} + A_{indirect}}{Energy} \left[\frac{ha * y}{TWh}\right]$$

Equation 3: Total land use intensity

$A_{footprint}$ = Footprint [*ha*]
OR
$A_{spacing}$ = Footprint [*ha*] + Spacing [*ha*]

Equation 4: Direct area definitions
(applicable energy systems: natural gas,
wind)

For two electricity sources (natural gas and wind), we offer two definitions of occupied land for our calculation of land use intensity: “footprint” and “spacing” area (Equation 4). Footprint area represents land directly covered by infrastructure, while spacing area is the entire area within the perimeter of a production site (further details in SI). For each electricity source, we included all individual LUIE values and calculated the median, average, standard deviation (SD), and interquartile range. To determine if our calculated LUIEs were statistically distinguishable, we performed an ANOVA with Tukey’s pairwise comparison.

Details on our data sourcing for each technology are provided below. A table summarizing the characteristics of the data in each source is provided in the Supplementary Information Table S1.

Coal: Total LUIE for coal (n = 30) includes direct land impacts from power plant infrastructure and indirect impacts from coal mining, processing, and transportation for the US and Canada. Several studies performed case studies or lifecycle analysis on a small number of coal power plants with varying technologies, including mining and transportation of fuel and waste disposal; these included Fthenakis & Kim (2009), Hertwich et al. (2015), Spitzley & Keoleian (2005), Smil (2010), and Gates (1985)[11,50–54]. Jordaan (2010) and McDonald et al. (2009) perform surveys of the land-use for coal mining in Canada and the US, respectively[12,55]. These two studies of indirect land-use were given in units of embodied energy for the mined coal, so we applied a 35% conversion efficiency to convert to electricity units, based on Ftheankis & Kim (2009)[11].

Natural Gas: Total LUIE for natural gas (n=17) includes direct impacts from power plant infrastructure and indirect impacts from natural gas drilling and transportation infrastructure. Footprint LUIE represents the area covered by gas well pads, access roads, and pipelines. Five sources provided data on footprint LUIE[16,51,55–57]. Spacing LUIE refers to the entire production field, including all the area in between well pads, even if that land does not have any structures or roads covering it. The US National Energy Technology Laboratory (2014) and US Department of Energy (1983) complete detailed life-cycle assessments for both direct and indirect land-use, including extraction, purification, pipeline transmission, and power plant[16,56]. Spitzley & Keoleian (2005) and Smil (2010) assess direct land-use through case studies of various natural gas power plants technologies[51,58]. Jordaan (2010) and Bryce (2011) provided figures only for indirect impacts from natural gas drilling for Canada and the US[55,57]. Jordaan et al. (2017) calculates lifecycle land use intensity for natural gas, from wells, to pipelines, to power plants[59]. McDonald et al. (2008) and Copeland et al. (2011) provided calculations for indirect spacing LUIE, assessing the area fragmented by natural gas drilling and pipelines[12,39].

Nuclear: Land use for nuclear includes direct impacts from the power plant and indirect impacts from the uranium fuel cycle, including mining, milling, conversion, enrichment, and fabrication. We collected original data for direct land-use for all operating nuclear power plants in the United States (n = 59), by drawing polygons around each power plant using Google Earth Pro. EIA provides data on each plant's electricity output[60]. Finch (1997), Eliasson & Lee (2003), Harries et al. (1997), and Schneider (2013) survey land area for uranium mining and processing[61–65], mostly in Australia, which averages 0.08 ha/TWh when we converted these per ton measurements into electricity units. Fthenakis & Kim (2009) was the only study that provides an estimate for the other aspects of the nuclear fuel cycle: conversion, enrichment, and fabrication[11]. Although they look only at uranium mining in the US, and find much higher land use intensity, roughly 4.0 ha/TWh. In the US, spent fuel is stored on-site and is therefore included in our direct LUIE calculation. We also estimated the additional land-use occupied by exclusion zones around the two major nuclear power accidents at Chernobyl in Ukraine (260,000 ha)[66], and Fukushima in Japan (63,000 ha)[67]. We calculated the LUIE of nuclear accidents by combining these two exclusion zones and dividing that area by total historical nuclear power generation (~82,000 TWh)[68], which resulted in an additional LUIE of 3.9 ha/TWh/y. However, in both cases, the exclusion zones are at least partially inhabited and, in the case of Chernobyl, the zone is occupied by abundant wildlife[69].

Hydroelectric: The direct area of hydroelectric dams is the area flooded by the reservoir. Our dataset (n = 962) is compiled from International Commission on Large Dam's (ICOLD) World Register of Dams database and represents single-use hydroelectric dams in eighty countries[70]. The World Register of Dams provided data on mean annual electricity and reservoir area. We exclude run-of-the-river hydroelectric projects since they represent a small portion (roughly 4%) of worldwide hydroelectric capacity and reliable generation data could not be found[71]. However, results from Fthenakis & Kim (2009) suggest LUIE for run-of-the-river projects are much smaller than for traditional hydroelectric (about 10 ha/TWh/y)[11].

Biomass: Like other combustibles, the land impacts from biomass include the direct area of the power plant as well as the area needed to supply the feedstock for the plant (indirect LUIE). Our dataset for dedicated biomass (n = 14) represents woody biomass production from willow, poplar, and spruce trees. Data are drawn from six sources[11–13,51,72,73]. For residue biomass, we assume no land requirement for feedstock production. Spitzley & Keoleian (2005), Fthenakis & Kim (2009), Kumar et al. (2003), and Smil (2010) provide generation and direct area information for various biomass plants[11,51,58,73]. Coal power plants can also be used as a proxy since it is common to retrofit a coal plant to burn biomass, but we would expect a biomass plant to have a larger LUIE since the plant runs at lower efficiency. Dijkman & Benders (2010), Kumar et al. (2003), and McDonald et al. (2009) calculate indirect land-use for biomass feedstock production looking at different crops[12,72,73].

Wind: While there are several studies of power density for wind farms (m^2/MW), we created an original dataset to calculate the land use intensity of existing wind farms using historic electricity generation data. Land impacts from wind come from the area covered by wind turbines and access roads. We calculate both footprint and spacing LUIE results for wind (n = 57). Footprint area represents only the area physically covered by the turbine pad and access roads; spacing area includes all the area in between turbines. Our dataset is generated from a randomized sample of operating US wind farms over 20 MW from EIA. We used EIA Form 860 and Form 923 to gather data on installed capacity and annual electricity output for each wind farm for 2013[74,75]. We combined this with measurements of the footprint and spacing area of each wind farm calculated using Google Earth Pro. For footprint area, we traced perimeters around each turbine pad and the access roads connecting them. For spacing area, we traced the perimeter of the entire wind farm, including all the space in between turbines.

Solar : We assessed the LUIE of integrated PV, ground-mounted PV, and solar CSP facilities. Integrated PV, which is 'integrated' into pre-existing structures in the built environment, is given a LUIE of zero in this study, since it does not have an additional land footprint. Our datasets for ground-mounted PV (n = 94) and CSP (n = 7) are based on existing, operational plants over 20 MW in 18 US states with capacity factors over 5%. For all sites, annual electricity generation data came from EIA Form 923 data for 2014[75]. Area measurements came from Hernandez et al. (n = 17)[30]; Ong et al. (n = 68)[14]; Solar Energy Industries Association (n = 12)[76]; and BLM (n = 3)[78]. For ground-mounted PV and solar CSP, we define direct area as the area of panels or heliostats, roads established during development, and all ancillary facilities. Ancillary facilities may include new service roads, power collection systems, communication cables, overhead and underground transmission lines, electrical sites, switchyards, project substations, meteorological towers, thermal storage units, and operations and maintenance facilities.

Geothermal: Geothermal land impacts include the area covered by power plant infrastructure and injection wells. Bertani (2005) provided a detailed list of worldwide geothermal power plants; however, their measured areas represented the entire expanse of the underground geothermal reservoir, only a fraction of which had aboveground land disturbance from the power plant and production wells[15]. We cross-referenced Bertani's generation data with land use data from geospatial measurements from the Global Energy Observatory (GEO) online database[79]. Our resulting dataset included 26 plants in 18 countries.

Application to Scenarios

The ten scenarios we assess are all global decarbonization pathways that make normative choices about energy demand, electrification rates, and energy technologies (see SI). The exception is

IEA's 6 degree scenario, which is a "business-as-usual" forecast. These scenarios vary in their assumptions about total electricity demand and the technology mix (see Supplementary Figure S1), as well as the end year of their projections (the JD scenario is for the year 2030[25], Brook is for 2060[26], and all others are for 2050). They were not selected based on economic or technical feasibility, but rather to represent a diverse range of future electricity scenarios, illustrating the possible land use implications of different decarbonization pathways. To determine the total land area required for electricity generation in the current (2017) and future scenarios, we multiplied the average LUIE result for each energy technology (in ha/TWh/y) by the amount of generation from that technology (in TWh/y) and summed totals over all electricity sources. Using the average LUIE provides a more accurate land use estimate when summing up over many sources, as using the median tends to underestimate total land use when multiplied by all energy consumption.

A thorough study of the land use implication for fossil- or biomass-fueled power plants with Carbon Capture and Storage (CCS) has yet to be performed, although data from Hertwich et al. suggest it would increase footprint by 40% compared to a plant without CCS. If a scenario included fossil or biomass generation with CCS, we multiplied our natural gas, coal, and biomass LUIEs by 1.4[50]. Electricity generation from oil combustion was included in some scenarios in very small quantities; we used the footprint LUIE from a natural gas plant for this figure, as estimates in the literature are not available.

To understand the significance of the differences across all future scenarios, we also propagated the errors (standard error of each energy source) through the total land use calculation to provide an uncertainty range for each scenario's total land use. In all scenarios, the uncertainty is dominated by the standard deviation in the LUIE of hydroelectric, which is large due to the regional variability of hydroelectric resources.

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Author contributions

J.L. conceived the idea for the study with input from T.N., L.B., M.S., and R.R.H; J.L. and M.S. implemented the research project; M.S., J.L., and R.R.H. collected the data; J.L., L.B., and R.R.H. analyzed the data; all authors contributed towards the writing of the paper.

Competing financial interests

The authors declare no competing financial interests.