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From Paris to practice: sustainable implementation of renewable energy goals

To cite this article: S Baruch-Mordo *et al* 2019 *Environ. Res. Lett.* **14** 024013

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OPEN ACCESS

RECEIVED

24 July 2018

REVISED

29 November 2018

ACCEPTED FOR PUBLICATION

6 December 2018

PUBLISHED

7 February 2019

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The signing of the Paris climate agreement and sustainable development goals demonstrated an international commitment to halting climate change, increasing energy access, and maintaining biodiversity. Successful implementation requires rapidly expanding renewable energy development, which has a large land footprint and can conflict with maintaining natural lands. To quantify the potential to mediate this land conflict, we converted emission reduction commitments submitted as part of the Paris agreement into actionable energy targets, and assessed whether they can be met by developing renewables on converted lands and waters of lower biodiversity and carbon value. The world has 19 times the required energy targets on converted lands, and most countries, including the top ten emitters, can meet the Paris agreement goals. Furthermore, regions (e.g. Africa) that will experience substantial population growth and that currently have limited energy infrastructure can meet their Paris agreement and future energy targets by developing renewable energy on already converted lands. Guiding renewable energy development to converted lands presents opportunities for sustainable development, but also requires incentives and proactive planning to ensure expansion does not exacerbate other environmental challenges.

1. Introduction

To safeguard global climate and maintain sustainable existence on Earth, scientists have urged humanity to quickly increase reliance on renewable energy and to halt the conversion of natural lands. In response to the imminent crises, countries signed the Paris Agreement (PA) at the 21st Conference of the Parties (COP21), with the goal of reducing greenhouse gas (GHG) emissions to keep global warming $<2^{\circ}\text{C}$ above pre-industrial levels. Nearly 200 countries submitted the now ratified Nationally Determined Contributions (NDCs) in which they specified GHG emission reduction targets (UNFCCC 2017), and at the upcoming COP24, the focus is on setting up guidance for NDCs implementation (UNFCCC 2018). Concurrently to the PA, countries committed to the UN Sustainable

Development Goals (SDGs) that include increasing sustainable energy access (SDG7) and halting and reversing land degradation (SDG15; United Nations 2015). Clearly, the international community is committed to halting climate change, increasing energy access, and maintaining biodiversity, but challenges remain for the successful implementation of the PA and SDGs.

Meeting the PA and SDGs climate mitigation and energy access commitments requires a multi-faceted approach with an increase in carbon capture and storage, energy efficiencies, and the transitioning of energy systems to renewable sources; the latter is often identified as key pathway to achieving goals (e.g. van Vuuren *et al* 2018). But because renewable energy development footprints are several folds greater than conventional energy sources (Gibson *et al* 2017,

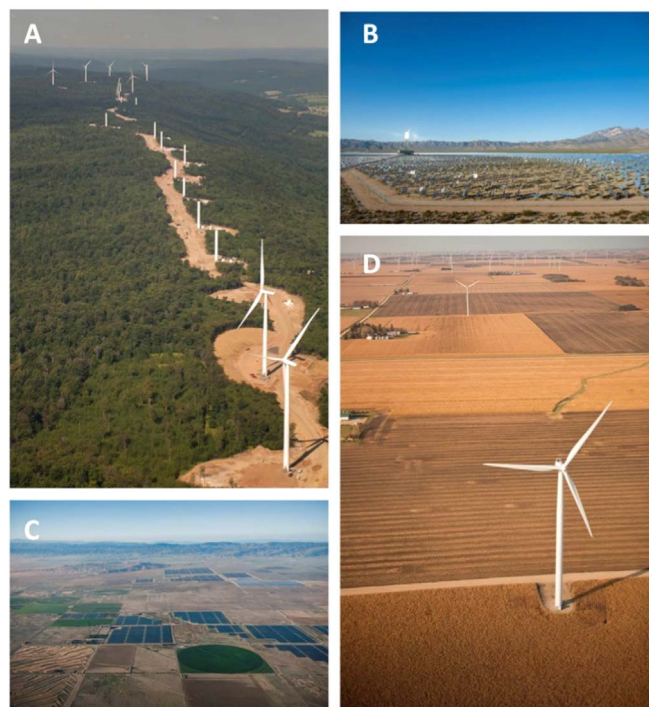


Figure 1. Wind and solar on natural and converted lands. Examples of wind and solar development displacing natural lands in (A) the Appalachian Mountains of the eastern US and (B) the Mojave Desert of the western US, and of integrated wind and solar development in already converted agricultural lands in the US states of (C) California and (D) Minnesota. Photo credits and rights are: (A) Mark Godfrey, (B)–(C) Dave Lauridsen, and (D) ColdSnap Photography.

Kiesecker and Naugle 2017), increasing the share of renewable energy can conflict with conserving natural lands (figures 1(A), (B); Santangeli *et al* 2016, Mccollum *et al* 2017). Maintaining intact natural lands is a major priority, with international initiatives to protect 17% of the world's natural lands by 2020 under the Aichi biodiversity targets (Secretariat of the Convention on Biological Diversity 2011), and the more recent call to protect 50% of natural lands under the Nature Needs Half movement (Dinerstein *et al* 2017). Protecting natural lands reduces the contribution of GHG emissions from land clearing, that currently contributes more than a third of global emissions (based on gross emissions; Houghton and Nassikas 2018). Furthermore, natural lands provide natural climate solutions and can deliver up to 37% of the CO₂ mitigation required by 2030 to hold global warming below the 2 °C target (Griscom *et al* 2017). Clearing natural lands for renewable energy development is therefore counterproductive to the fulfillment of the PA and SDGs.

Here we assessed whether converted lands, defined as terrestrial landscapes or freshwater systems already impacted by human activities (e.g. human settlements, agriculture lands, roads, and dams), can meet renewable energy targets derived from the PA emission reduction goals. Relative to more pristine natural areas, converted lands often have lower value to biodiversity (Newbold *et al* 2015) and carbon storage and sequestration (Griscom *et al* 2017). While other studies have estimated the renewable energy potential on terrestrial lands (e.g. Zhou *et al* 2012, Köberle *et al*

2015) and freshwater systems (e.g. Gernaat *et al* 2017), or assessed potential conflicts between renewable energy potential and protected area goals (Santangeli *et al* 2016), to our knowledge none have evaluated whether demands can be exclusively met on converted lands and waters. We converted NDC emission reductions into energy targets (TWh; hereafter also referred to as NDC energy targets), estimated the technical potential of wind, solar and hydropower renewable energy on converted terrestrial lands and freshwater systems, and evaluated globally and by country, whether NDC energy targets can be met by developing renewable energy on already converted lands and waters.

2. Methods

2.1. Quantifying NDC emission reductions

We derived the amount of GHG emission reductions (MtCO₂eq) by multiplying reduction goals (%) by the NDCs-specified reference emissions (supplementary data is available online at stacks.iop.org/ERL/14/024013/mmedia). We included NDCs submitted up to May 2016, and we refer to intended (INDC) and ratified (NDC) submissions collectively as NDCs. We wished to remain conservative in our evaluation of renewable energy credits on converted lands, hence we obtained the largest emission reduction commitments; this entailed using conditional NDC goals, i.e. dependent on international assistance, that were larger

and more ambitious; additionally this often entailed using past reference emissions that included Land Use, Land Use Change and Forestry emissions.

Each country provided different past or future reference year for their emission reduction commitments, which we detail in supplementary data S1. We collated % reduction goals from three sources: (1) the NDC & INDC FactSheets (hereafter FactSheets) created by the Australian–German Climate and Energy College (Meinshausen and Alexander 2016), (2) Rogelj *et al* (2016), and (3) UNEPLive (2017). For countries referencing historic GHG emissions, we used historic emissions data available in the FactSheets ($n = 51$), or emissions based on the AR4 model for Kyoto greenhouse gases from PRIMAP-HIST database (Gutschow *et al* 2016) ($n = 13$). For countries referencing business-as-usual (BAU) GHG emission projections ($n = 81$), we used FactSheets projected data (based on SAR, AR4, or AR5 models). We visually estimated BAU emissions from the inserted graphic if no numeric estimate was explicitly included (Costa Rica and South Africa; supplementary data S1). For countries committing to reduction goals in emission intensity (i.e. emissions per GDP; $n = 6$), we either used published GHG emission estimates for BAU and NDC-implemented emission scenarios (den Elzen *et al* 2016) and calculated their difference to obtain the amount of abated emissions (China, India), or we used past emissions and projected GDP data to derive emission reductions as detailed in section 2 of the supplementary information (Chile, Malaysia, Singapore, and Tunisia). Additional country-specific exceptions and calculations to derive reduction goals and abated emissions are detailed in supplementary data S1.

2.2. Calculating NDC energy targets

We used the NDC emission reductions to calculate the amount of energy in TWh that is needed to offset electricity and heat generation from fossil fuel into renewable energy in order to meet emission reduction goals. Using World Bank data (2017; % CO₂ emissions from electricity and heat production), we first calculated the proportion of NDC emission reduction commitments (MtCO₂eq) related to heat and electricity production, assuming those could feasibly be converted from fossil fuels to renewable energy. We note that estimating the required energy to convert other sectors (e.g. transportation) to renewable energy was beyond the scope of this paper, but was explored using data from Jacobson *et al* (2017) as detailed in section 3. Because not all countries were included in the World Bank data for ‘% CO₂ emissions from electricity and heat production’, our sample size after this step consisted of 110 countries (figure S1).

We then converted the amount of emissions from electricity and heat in MtCO₂eq into TWh using the inverse, median, sector-specific, IPCC life cycle

emission conversion factors (*lce*; Moomaw *et al* 2011, Schlömer *et al* 2014). *Lce* are reported for each energy sector as gCO₂eq/kWh (e.g. oil –840, coal –820, and gas –490), and represent the total emissions per unit of energy that is associated with the life of a power plant including, component production, plant construction, and operations (Krey *et al* 2014). Because *lce* are sector-specific, we first calculated the proportion of electricity and heat emissions that are attributed to each fossil fuel energy sectors (oil, coal, and gas) using 2014 IEA energy production statistics (IEA 2017a). Then for each fossil fuel sectors, we multiplied their proportional MtCO₂eq emissions by the sector’s inverse *lce* (kWh/gCO₂eq), which we converted to TWh/MtCO₂eq for unit cancellation. The result was TWh associated with each fossil fuel sector if we converted their proportion of NDC emission reductions into renewable energy targets, and we summed across all fossil fuel sectors to obtain the total NDC energy target for each country. We note that Albania had already produced 100% of its electricity and heat from renewable energy, hence we did not include it in the analyses to convert emissions into renewable sources. Therefore our final sample size consisted of 109 countries (figures S1 and S2A), which included top GHG emitters and accounted for 92% of global GHG emissions (Gutschow *et al* 2016). Additionally the collective NDC energy targets of 9 017 TWh from the 109 countries were equivalent to 41% of 2014 world electricity consumption (IEA 2017a).

2.3. Renewable energy technical potential

We spatially estimated wind and solar renewable energy potential on converted lands, and augmented these estimates with the potential to increase hydropower generation on already converted freshwater systems (hereafter collectively referred to as renewable energy on converted lands for brevity). We focused on wind and solar sectors because they have already penetrated the market and are projected to consist of 80% of global capacity growth in the next five years, and on hydropower because it is projected to remain the leading source of renewable electricity generation in the near-term (IEA 2017b). We excluded the bioenergy sector because of its high potential to displace croplands and natural lands (Smith *et al* 2010); the geothermal sector that has a much smaller global potential (Gibson *et al* 2017); and the marine-based sectors (off-shore wind, tidal, and wave) for which an analogous approach for identifying converted areas is not straightforward. All spatial data were projected to Mollweide, resampled to 1-km raster resolution as required using bilinear (continuous data) or nearest-neighbor (discrete data) methods, and snapped to a common mask. Analyses were conducted in ArcGIS v10.3.1 (ESRI 2015) and Program R v3.3.2 (R Core Team 2016).

For wind and solar, we spatially estimated technical potential on terrestrial converted lands for utility-scale wind, concentrated solar power (CSP), and photovoltaics (PV), and for rooftop PV as generally described below, and in detail for each sector in supplementary information. We defined terrestrial lands using the European Space Agency's climate change initiative land cover data (v1.6.1 for the 2008–2012 epoch European Space Agency 2017) by excluding water and permanent snow and ice. We additionally excluded world protected areas of categories I–III (IUCN 2017) for all sectors, and for utility-scale sectors, we also excluded urban areas (Schneider *et al* 2009) where utility-scale development is less likely to occur. Following Oakleaf *et al* (2015), we defined converted terrestrial lands at a 1-km resolution as any cell with: (1) value >0 for the most recently (2013) available raster of nighttime lights (NOAA 2017), (2) $>0\%$ agricultural lands based on the Unified Crop Layer (v2.3; Waldner *et al* 2016), or (3) any road mapped in gROADSv1 (Center for International Earth Science Information Network - CIESIN - Columbia University, and Information Technology Outreach Services - ITOS - University of Georgia 2013). Cells not meeting these criteria were considered natural terrestrial lands. We estimated sector-specific technical potential (MW) using: $\sum A_i \cdot CF_i \cdot P$, where for each cell i , A_i is the total area (km^2) that is suitable for development based on resource and other biophysical constraints, CF_i is the capacity factor, or the ratio of the actual output of power over the rated capacity, and P is the non-spatially explicit sector's power density (MW/km^2), or its inverse land use requirements. We note that for wind, CSP, and utility-scale PV, A_i will always equal 1 km^2 if the cell is suitable for development based on detailed constraints, but for rooftop PV, A_i will always be $<1 \text{ km}^2$ given our assumption that usable roof area is always $<100\%$ (see supplementary information section 1 for details). We selected parameters based on published literature and empirically derived parameter values where data were available (details in supplementary information section 1 and table S1). Energy totals (MW) were converted to TWh by multiplying by 8760 (hours per year) and dividing by 10^6 (MW per TW).

For hydropower, we restricted the definition of already converted freshwater systems to sites with existing dams, as new dams on previously undammed sites will almost always impact natural river processes (e.g. flow patterns or connectivity; Winemiller *et al* 2016, Gibson *et al* 2017). Therefore, we estimated the potential TWh from retrofitting old hydropower dams with more efficient equipment, or from repurposing non-hydroelectric dams by adding power generating turbines (details in supplementary information). Individual dam hydroelectric capacity data were not spatially available; however we obtained from the International Hydropower Association a country-specific decadal summary of hydroelectric capacity.

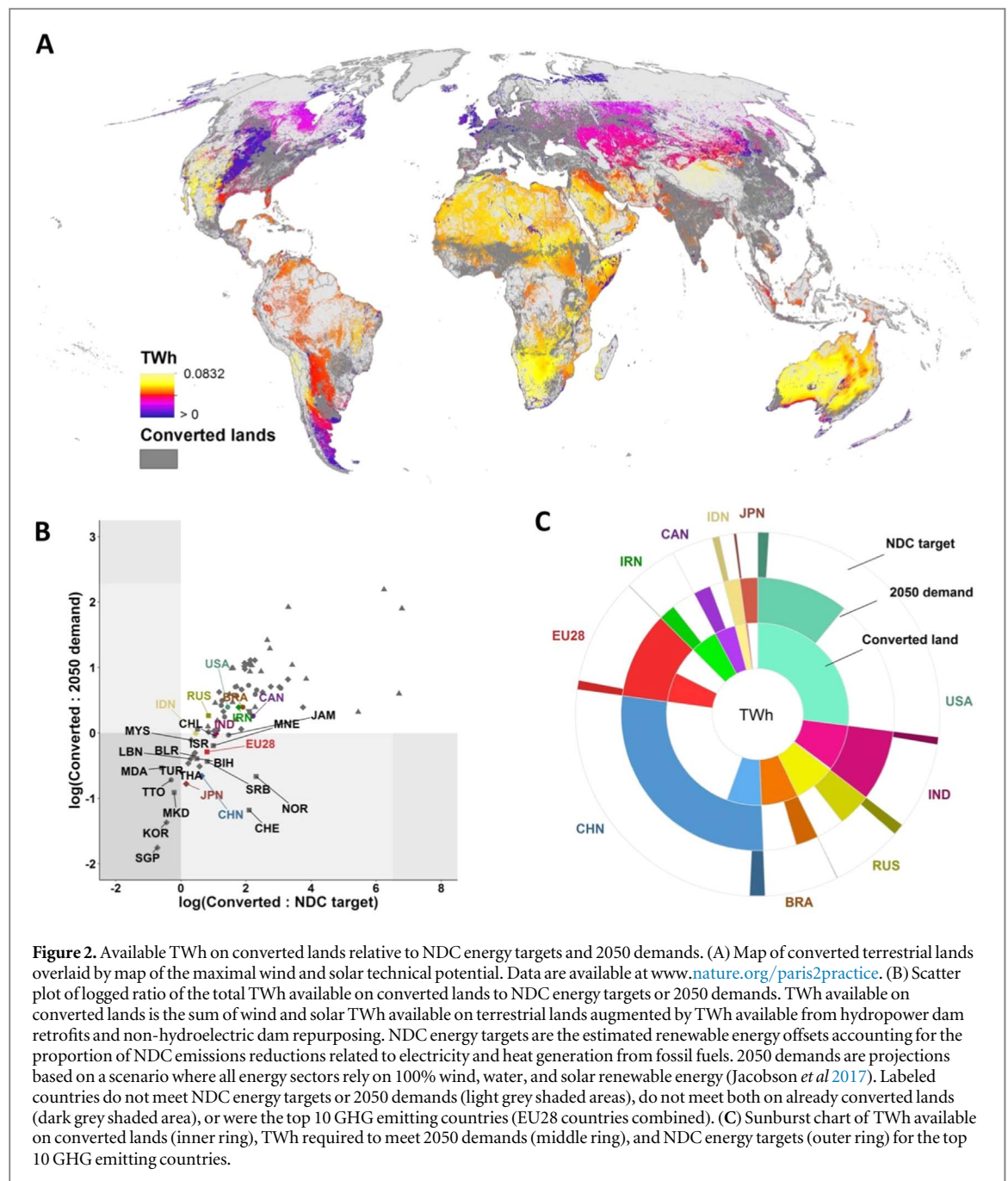
We considered retrofitting dams that have been in service for 30 years or longer (IEA 2012), and conservatively assumed 10% increase in efficiency (table S1). To estimate repurposing technical potential, we selected non-hydroelectric dams from the GRanD global dam database (Lehner *et al* 2011), and using available parameters of dam height and average discharge, calculated the TWh potential that each repurposed dam can produce (supplementary information section 1).

2.4. Renewable energy credits and deficits

Once we estimated the available TWh on converted lands and freshwater systems, we assessed whether each country could meet its NDC energy targets. To avoid double counting and overestimation of energy potential on terrestrial lands when a cell had potential for more than a single sector (figures S3, S4), we created a final TWh output map by selecting for each cell the value from the sector with the maximum TWh across all land-based wind and solar sectors. Using this maximal renewable energy map (figure 2(A)), we summed the total available TWh on converted lands for each country, and augmented this sum with TWh from new hydropower dam retrofits and non-hydroelectric dam repurposing. We then calculated ratio of TWh on converted lands and freshwater systems to NDC energy targets.

3. Results and discussion

Converted lands for the 109 countries included in our analyses (figures S1 and S2A) encompassed 83% of total terrestrial lands. After removing areas unsuitable for renewable energy development (e.g. areas that are protected, have low energy resource value, contain biophysical constraints, or experience high multi-use competition; see supplementary information), we estimated that 168 589 TWh technical potential are available on converted lands (figure 2(A)) from wind (11 616 TWh, figure S3A, supplementary data S2) and solar (CSP: 61 340 TWh, PV: 92 512 TWh, and rooftop PV: 3 121 TWh, figure S3(B), (C), supplementary data S2). With additional gains from retrofitting of existing dams (134 TWh) and repurposing of non-hydroelectric dams (88 TWh), a total of 168 811 TWh are available. While five countries (Macedonia, Moldova, Singapore, South Korea, Trinidad and Tobago) cannot meet their NDC commitments on converted lands (figure 2(B)), the total global TWh available on converted lands is 19 times larger than the total NDC energy targets (9 017 TWh; supplementary data S2). Furthermore all top ten GHG emitting countries (classifying the EU28 collectively), which accounted for 71% of global emissions in 2014 (Gutschow *et al* 2016), can meet their NDC targets by developing renewable energy on already converted lands (figure 2(C), supplementary data S2).



Given that the PA commitments are insufficient to maintain global warming $<2^{\circ}\text{C}$ pre-industrial levels, and that achieving zero and even negative GHG emissions are required (Rogelj *et al* 2016), we further explored whether countries ($n = 139$; figure S2B) can meet 2050 energy demands on converted lands under a published scenario of 100% future reliance on renewable energy by all sectors, not just electricity and heat production (Jacobson *et al* 2017). While we recognize that these demand projections may be over-optimistic in allocation of all consumer sectors' demands to renewable energy and have other limitations, we encouragingly found that current converted lands have nearly twice the amount of technical potential (185 827 TWh) than the 2050 projected demands (103, 716 TWh). Regionally, African countries that

will experience substantial population growth and have limited energy infrastructure (IEA 2017c), have many times the renewable energy potential compared to their projected demands (supplementary data S2). By 2030, 89% of the global population without electricity access will reside mostly in rural sub-Saharan Africa (IEA 2017c). Therefore, African countries have a unique opportunity to proactively site renewable energy on converted lands in a distributed manner, i.e. close to the consumer, thereby providing energy access to rural population (SDG7) while minimizing transmission costs and environmental impacts.

Despite the encouraging global and regional results, country-specific analyses reveal that 57 countries are unable to meet 2050 energy demands solely on converted lands, including five of the top ten GHG

emitters (China, EU28, Japan, India, and Indonesia; supplementary data S2, figure 2(B), (C)). It is likely that some of the countries highlighted as unable to meet NDC and future energy targets may succeed in doing so especially as converted lands are projected to increase by up to 2.23 million km² (Lambin and Meyfroidt 2011), or ~6% of this study's estimate of converted lands (37.85 million km²), and that the percent of usable converted lands can increase with the increased deployment of integrated electricity and heat generation technology (e.g. solar pavement (Dezfooli *et al* 2017) and building-integrated solar thermal (Maurer *et al* 2016)). Nevertheless, expanding and incentivizing cross-border coordination of electricity interconnection may be necessary to meet demands. Examples include China's inter-regional and inter-provincial exchanges that consist of 15.9% of electricity consumption (Hurlbut *et al* 2017), and the European Commission's energy roadmap which set a target goal of 15% interconnections by 2030 (Dutton and Lockwood 2017). Coordinated planning for power generation, transmission, and exchanges, and adequate pricing, trading, and regulatory mechanisms are key to cross-border integration of renewable energy generated on converted lands (Dutton and Lockwood 2017, Hurlbut *et al* 2017, Mehling *et al* 2018).

Nine times as much wind and solar development will be required to meet the NDC energy targets of ~9000 TWh relative to their current electricity and heat generation of ~1000 TWh worldwide (IEA 2017a). Siting renewable energy in an unrestricted manner that displaces natural lands (e.g. figures 1(A), (B)) can result in carbon and therefore emission losses corresponding to ~8% of the total PA emission reduction commitments (Kiesecker *et al in Review*). Furthermore, estimating the time it would take to offset these losses from natural land clearing for renewable energy suggests that in some regions such as the EU28, over 50% of renewable energy development could require >2.5 years of generation to make up for carbon and emission losses (Kiesecker *et al in Review*); a critical timeframe when emissions should peak by 2020 to keep global warming <2 °C (Figueres *et al* 2017). Advancing renewable energy under a development strategy that targets already converted lands holds the potential to avoid the negative impacts to natural lands. With the exception of bioenergy that can displace croplands (Smith *et al* 2010), renewable energy development can be compatible with other human land uses (e.g. agriculture and urban; figures 1(C), (D); Hernandez *et al* 2015, Burt *et al* 2017) and offer economic benefits. For example, farmers in the United States may receive \$4000–\$8000 USD annually per turbine when leasing cropland to wind energy development (Burt *et al* 2017), and siting renewable energy on converted lands near demand centers reduces transmission cost (Drechsler *et al* 2017), which

could otherwise be a barrier to renewable energy development (Fischlein *et al* 2013).

Given the global extent of our analysis, we undertook a somewhat simplified approach to estimating renewable energy technical potential on converted lands, and our analyses have three main sources of uncertainty relating to: quantification of NDC energy targets, definition of converted lands, and estimation of renewable energy potential. By focusing on decarbonizing energy generation from electricity and heat sources, we accounted for roughly a third (5.97 GtCO₂eq) of the quantifiable NDC emission reduction targets (17.68 GtCO₂eq; supplementary figure S1, supplementary data S1), potentially underestimating energy needs. However, we may also underestimate energy potential given that our binary definition of converted and unconverted lands may exclude other human activities (e.g. livestock grazing, logging, recreation) that make semi-natural lands more suitable for renewable energy development without adverse impacts to biodiversity and carbon storage. Furthermore, augmenting energy potentials with excluded sectors and considering concurrent, rather than mutually-exclusive, development of multiple sectors in a given location (e.g. siting both wind and solar in a given cell) will increase the energy potential of converted lands.

Beyond the uncertainty considerations stated above, our study included additional limitations. First, we did not exclude existing power plants from future development thereby potentially overestimating the available technical potential on converted lands. We post hoc explored this overestimation potential using global datasets for existing CSP and wind turbines (no global data were available for PV) and found such overestimation is marginal at best, with existing CSP and wind installations respectively accounting for 0.0007% and 0.076% of the total estimated renewable energy on converted lands (see details in supplementary information section 4). Second, because we wished to be conservative in estimating technical potential on converted lands, we used only one set of parameters associated with lowest power output and did not conduct a sensitivity analysis exploring combinations across parameters' space (that likely would have inflated available technical potential on converted lands). Finally we relied on static maps of available technical potential that were based on annual averages that smooth over the variability of renewable energy sources and their ability to provide reliable energy at all times. More complex methodologies and models that incorporate the dynamics of renewable energy availability, and address issues including meeting peak consumer demands or accounting for transmission and distribution losses, are priorities for future research. Ultimately, a localized and comprehensive energy systems analysis that incorporates cost-effective integration of variable renewable energy while optimizing over multiple objectives in the

climate-energy-biodiversity nexus, should be incorporated into best practices for PA and SDGs implementation.

4. Conclusions

Given its larger land footprint and the negative climate and biodiversity consequences of poor renewable energy siting, it will be critical to ensure that future development is preceded by the necessary planning and incentive mechanisms to minimize its impacts. Land management could be an important component of climate mitigation (Houghton and Nassikas 2018), with opportunities to site renewable energy on converted lands especially in developing countries such as African nations with sparse existing infrastructure and that anticipate substantial population growth. Targeting subsidies to favor low-impact developments, and creating avoidance and mitigation requirements that raise the costs for projects impacting natural lands, are two possible pathways to steer renewable energy development to converted lands. Failure to do so could lead to greater risk for investors and could set back progress in attaining the commitments of the PA and SDGs.

Acknowledgments

We thank The Nature Conservancy, Anne Ray Charitable Trust, and Enterprise Foundation for funding this research. We thank Mark Mehos and Paul Veers of the National Renewable Energy Laboratory, Steve Smith of the Pacific Northwest National Laboratory, Joeri Rogelj of the International Institute for Applied Systems Analysis, Boualem Hadjerioua of Oak Ridge National Laboratory, and Norman Bishop of Knight Piésold Consulting for valuable input on data availability and methodology, Vaisala for providing 3TIER wind and solar resource data, and the International Hydropower Association for providing global hydropower capacity data. We thank Josh Goldstein and other anonymous reviewers that helped improve this manuscript. With immense gratitude we thank Moshe Mordo for his support throughout this effort.

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References

- Burt M, Firestone J, Madsen J A, Veron D E and Bowers R 2017 Tall towers, long blades and manifest destiny: the migration of land-based wind from the Great Plains to the thirteen colonies *Appl. Energy* **206** 487–97
- Center for International Earth Science Information Network - CIESIN - Columbia University, and Information Technology Outreach Services - ITOS - University of Georgia 2013 Global Roads Open Access Data Set, Version 1 (gROADSv1). (Palisades, NY: NASA Socioeconomic Data and Applications Center) (<https://doi.org/10.7927/H4VD6WCT>)
- den Elzen M, Admiraal A, Roelfsema M, van Soest H, Hof A F and Forsell N 2016 Contribution of the G20 economies to the global impact of the Paris agreement climate proposals *Climate Change* **137** 655–65
- Dezfooli A S, Nejad F M, Zakeri H and Kazemifard S 2017 Solar pavement: a new emerging technology *Sol. Energy* **149** 272–84
- Dinerstein E *et al* 2017 An ecoregion-based approach to protecting half the terrestrial realm *Bioscience* **67** 534–45
- Drechsler M, Egerer J, Lange M, Masurowski F, Meyerhoff J and Oehlmann M 2017 Efficient and equitable spatial allocation of renewable power plants at the country scale *Nat. Energy* **6** 17124
- Dutton J and Lockwood M 2017 Ideas, institutions and interests in the politics of cross-border electricity interconnection: Greenlink, Britain and Ireland *Energy Policy* **105** 375–85
- ESRI 2015 ArcGIS for Desktop: Release 10 (Redlands, CA: Environmental Systems Research Institute)
- European Space Agency 2017 Climate Change Initiative - Land Cover (<https://esa-landcover-cci.org/>)
- Figueres C, Schellnhuber H J, Whiteman G, Rockström J, Hobley A and Rahmstorf S 2017 Three years to safeguard our climate *Nature* **546** 593–5
- Fischlein M, Wilson E J, Peterson T R and Stephens J C 2013 States of transmission: moving towards large-scale wind power *Energy Policy* **56** 101–13
- Gernaat D E H J, Bogaart P W, van Vuuren D P, Biemans H and Niessink R 2017 High-resolution assessment of global technical and economic hydropower potential *Nat. Energy* **2** 821–8
- Gibson L, Wilman E N and Laurance W F 2017 How green is 'green' energy? *Trends Ecol. Evol.* **32** 922–35
- Griscom B W *et al* 2017 Natural climate solutions *Proc. Natl Acad. Sci.* **114** 11645–50
- Gütschow J, Jeffery M L, Gieseke R, Gebel R, Stevens D, Krapp M and Rocha M 2016 The PRIMAP-hist national historical emissions time series *Earth Syst. Sci. Data* **8** 571–603
- Hernandez R R, Hoffacker M K, Murphy-Mariscal M L, Wu G C and Allen M F 2015 Solar energy development impacts on land cover change and protected areas *Proc. Natl Acad. Sci.* **112** 13579–84
- Houghton R A and Nassikas A A 2018 Negative emissions from stopping deforestation and forest degradation, globally *Glob. Chang. Biol.* **24** 350–9
- Hurlbut D, Zhou E, Bird L and Wang Q 2017 *Transmission Challenges and Best Practices for Cost-Effective Renewable Energy Delivery across State and Provincial Boundaries* National Renewable Energy Lab, Golden, CO NREL/TP-6A20-69067
- International Energy Agency 2012 *Technology roadmap hydropower* International Energy Agency, Paris
- International Energy Agency 2017a Statistics (www.iea.org/classicstats/statisticssearch/)
- International Energy Agency 2017c *Energy Access Outlook 2017: From Poverty to Prosperity* (https://iea.org/publications/freepublications/publication/WEO2017SpecialReport_EnergyAccessOutlook.pdf)
- International Energy Agency 2017b *Renewables 2017 Analysis and Forecasts to 2022* (<http://iea.org/media/publications/mtrmr/Renewables2017ExecutiveSummary.PDF%0Ahttp://www.iea.org/media/publications/mtrmr/Renewables2017LaunchPresentation.pdf>)
- International Union for Conservation of Nature 2017 World database on protected areas (WDPA) (<https://iucn.org/theme/protected-areas/our-work/quality-and-effectiveness/world-database-protected-areas-wdpa>)
- Jacobson M Z *et al* 2017 100% clean and renewable wind, water, and sunlight all-sector energy roadmaps for 139 countries of the world *Joule* **1** 108–21

- Kiesecker J M, Baruch-Mordo S, Kennedy C M, Oakleaf J R, Baccini A and Bronson G W Hitting the target but missing the mark: unintended consequences of the Paris climate agreement *Cons. Lett.* (in preparation)
- Kiesecker J M and Naugle D E 2017 *Energy Sprawl Solutions: Balancing Global Development and Conservation* (Washington, DC: Island Press)
- Köberle A C, Gernaat D E H J and van Vuuren D P 2015 Assessing current and future techno-economic potential of concentrated solar power and photovoltaic electricity generation *Energy* **89** 739–56
- Krey V *et al* 2014 Annex II: Metrics & Methodology *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O Edenhofer *et al* (Cambridge: Cambridge University Press)
- Lambin E F and Meyfroidt P 2011 Global land use change, economic globalization, and the looming land scarcity *Proc. Natl Acad. Sci.* **108** 3465–72
- Lehner B *et al* 2011 High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management *Front. Ecol. Environ.* **9** 494–502
- Maurer C, Cappel C and Kuhn T E 2016 Progress in building-integrated solar thermal systems *Sol. Energy* **154** 158–86
- Mccollum D, Echeverri G L and Riahi K and Parkinson S 2017 SDG7 ensure access to affordable, reliable, sustainable and modern energy for all *A Guide to SDG Interactions: From Science to Implementation* ed D J Griggs *et al* (Paris: International Council for Science) pp 127–73
- Mehling M A, Metcalf G E and Stavins R N 2018 Linking climate policies to advance global mitigation *Science* **359** 997–8
- Meinshausen M and Alexander R 2016 *NDC & INDC Factsheets* Climate and Energy Collage, The University of Melbourne (<http://climatecollege.unimelb.edu.au/ndc-indc-factsheets>)
- Moomaw W, Burgherr P, Heath G, Lenzen M, Nyboer J and Verbruggen A 2011 Annex II: Methodology *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* ed O Edenhofer *et al* (Cambridge: Cambridge University Press) (<http://ncbi.nlm.nih.gov/pubmed/25180255>)
- National Oceanic Atmospheric Administration 2017 Version 4 DMSP-OLS Nighttime Lights Time Series (<https://ngdc.noaa.gov/eog/dmsp/downloadV4composites.html>)
- Newbold T *et al* 2015 Global effects of land use on local terrestrial biodiversity *Nature* **520** 45–50
- Oakleaf J R, Kennedy C M, Baruch-Mordo S, West P C, Gerber J S, Jarvis L and Kiesecker J 2015 A world at risk: aggregating development trends to forecast global habitat conversion *PLoS One* **10** e0138334
- R Core Team 2016 R: A language and environment for statistical computing (Vienna: R Foundation for Statistical Computing) (<https://r-project.org/r-project.org/>)
- Rogelj J, den Elzen M, Höhne N, Fransen T, Fekete H, Winkler H, Schaeffer R, Sha F, Riahi K and Meinshausen M 2016 Paris agreement climate proposals need a boost to keep warming well below 2 °C *Nature* **534** 631–9
- Santangeli A, Toivonen T, Pouzols F M, Pogson M, Hastings A, Smith P and Moilanen A 2016 Global change synergies and trade-offs between renewable energy and biodiversity *GCB Bioenergy* **8** 941–51
- Schlömer S *et al* 2014 Annex III: Technology-Specific Cost and Performance parameters *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O Edenhofer *et al* (Cambridge: Cambridge University Press)
- Schneider A, Friedl M A and Potere D 2009 A new map of global urban extent from MODIS satellite data *Environ. Res. Lett.* **4** 44003
- Secretariat of the Convention on Biological Diversity 2011 Strategic Plan for Biodiversity 2011–2020 and the Aichi Targets (United Nations) (<https://cbd.int/sp/>)
- Smith P, Gregory P J, van Vuuren D, Obersteiner M, Havlik P, Rounsevell M, Woods J, Stehfest E and Bellarby J 2010 Competition for land *Philos. Trans. R. Soc. B Biol. Sci.* **365** 2941–57
- UNEP Live 2017 Emissions-Impact-Climate Change *United Nations Environment Programme* (<https://pre-uneplive.unep.org/theme/index/13#indcs>)
- UNFCCC 2018 24th Conference of the Parties to the United Nations Framework Convention on Climate Change (Katowice, Poland 3 December–14 December 2018) (<http://cop24.gov.pl/>)
- UNFCCC 2017 Paris Agreement Status of Ratification 1–2 (United Nations Climate Change) (<https://unfccc.int/process/the-paris-agreement/status-of-ratification>)
- United Nations 2015 Sustainable Development Goals (<https://un.org/sustainabledevelopment/sustainable-development-goals/>)
- van Vuuren D P *et al* 2018 Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies *Nat. Clim. Chang.* **8** 391–7
- Waldner F *et al* 2016 A unified cropland layer at 250 m for global agriculture monitoring *Data* **1** 3
- Winemiller K O *et al* 2016 Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong *Science* **351** 128–9
- Zhou Y, Luckow P, Smith S J and Clarke L 2012 Evaluation of global onshore wind energy potential and generation costs *Environ. Sci. Technol.* **46** 7857–64