



Minimizing Impacts of Future Renewable Energy Development on the World's Desert Ecosystems

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Renewable energy development is rapidly increasing across the world, providing affordable and more environmentally sustainable energy to many populations. However, renewable energy, such as solar and wind, can have large land footprints through conversion and modification of natural habitats. One of the more intact habitats on Earth is the desert biome, which contains large areas of roadless regions and, in some places, high biodiversity. Since they are often windy and sunny, desert regions also tend to be rich in renewable energy resources. Using publicly available geospatial data, we calculated that the highest resource areas for wind overlap with 79% of roadless areas and the highest resource areas for solar overlap 28% of roadless areas, globally. High resource wind and solar areas overlap high plant diversity regions by 56 and 79%, respectively, but because high plant diversity desert areas are localized, these overlap areas represent a tiny proportion of the total potentially economically valuable wind and solar regions. These results suggest that desert regions remaining ecologically intact are at risk from renewable energy development. However, strategic siting in abundant, lower quality desert areas might mitigate this issue, especially when areas already impacted by human activity are available. Selected regions presented in detail demonstrate the risks to these habitats and strategies to minimize ecosystem damage. We urge governments and industries to consider placement of wind and solar energy projects that minimize environmental impacts to lands that, up to this point, remain relatively untransformed by human activities.

Keywords: biodiversity, deserts, renewable energy, roadless areas, solar power, wind power

INTRODUCTION

The global energy industry is changing rapidly, with new production of renewable energy sources growing at a faster rate than traditional fossil fuels (International Energy Agency, 2021). Some fossil fuels, such as coal, appear to be in terminal decline (Mendelevitch et al., 2019), and efforts are underway in some countries to reduce oil and gas use as a way to address global climate change (Le Quéré et al., 2019). The most prominent renewable sources being developed are wind and solar, whose production has grown exponentially in the last decade (Moriarty and Honnery, 2019). While solar and wind power have limited carbon emissions, they still can have important impacts on land-use, fragmentation, and ecosystem services provision by natural habitats (McDonald et al., 2009; Hernandez et al., 2015; Grodsky and Hernandez, 2020; Rehbein et al., 2020). In some cases, solar and wind power can have comparable levels on land-use impact as some fossil fuel generation,

at least in the short-term (Jordaan et al., 2021). Finding ways to mitigate this impact on natural ecosystems will be of prime importance as these renewable sources continue to expand.

Deserts cover about 13% of the Earth's surface (Costanza et al., 2014) and remain some of the least developed regions on the planet (McClung et al., 2019), partly because they are generally unsuitable for intensive agriculture, the largest historical driver of land use change (Kanianska, 2016) until recent times (Trainor et al., 2016). While deserts may be low productivity environments, they can contain high species diversity and have high rates of endemism (Johnston, 1977; Safriel et al., 2005). Some deserts represent globally important biodiversity hotspots (e.g., Karoo of South Africa and the Sonoran/Chihuahuan regions of the U.S. and Mexico; Myers et al., 2000) and support vibrant human cultures while providing numerous local and global ecosystem services (Mucina et al., 2006; Durant et al., 2012, 2014; Dimmitt et al., 2015; Taylor et al., 2017; McClung et al., 2019). Because of the generally low human population density, deserts remain some of the least fragmented habitats, allowing landscape level ecological interactions to continue in a time when most other habitats are highly fragmented and modified (Jacobson et al., 2019).

While deserts remain mostly intact, new threats are emerging that could drastically alter these lands (Hernandez et al., 2015). The world is beginning an energy transition from fossil fuels to renewable sources (Cameron et al., 2017; Ram et al., 2020; Luderer et al., 2022), with wind and solar being two important and rapidly expanding methods, in some cases already having impacts on high biodiversity areas (Rehbein et al., 2020). Deserts are, by their nature, generally sunny and windy, so it is not surprising that much solar and wind development has occurred (and continues to occur) in desert ecosystems (Copeland et al., 2011; McClung et al., 2019). For example, the American Southwest arid lands have become major suppliers of power to the U.S. electrical grid in recent years (Parker et al., 2018). In some cases, these renewable energy developments have occurred in areas that previously lacked significant industrial activity (Parker et al., 2018; McClung et al., 2019).

While deserts have ubiquitous solar and wind potential, it is unlikely that these resources are dispersed uniformly in the environment (McClung et al., 2019). The same pattern holds true for biological and ecological resources. Biodiversity and unmodified desert habitat are likely to be aggregated in relatively smaller areas compared to the vast coverage of deserts (Durant et al., 2012), similar to patterns seen in other major biomes (Myers et al., 2000). If emerging renewable energy development could be sited in a way that avoids the most valuable desert regions, future energy needs could be met while minimizing losses to biological, ecological, and cultural resources. The goal of this study was to identify the most intact and biologically valuable desert environments globally by examining plant biodiversity and roadless patterns. We then sought to identify the best wind and solar resources in deserts to determine where they overlap the most ecologically valuable desert regions. Our hope is that by identifying these desert areas of high risk, recommendations could be made on where to steer renewable energy development to minimize impacts on biodiversity and unfragmented habitats.

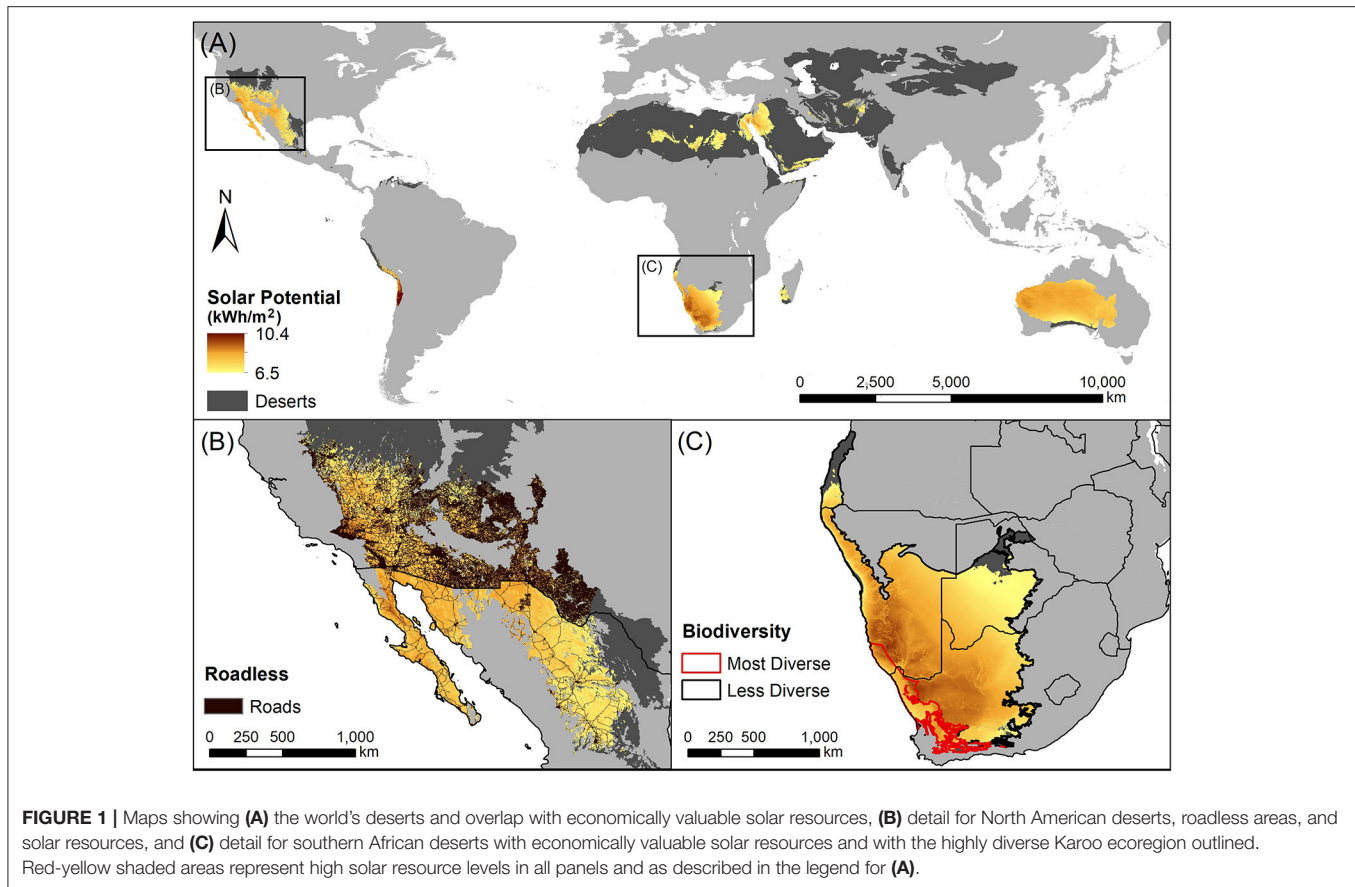
MATERIALS AND METHODS

To answer the question of where the highest quality desert habitat remains and its risk for future development, we first had to define our quality and risk factors. We used two conservation categories to identify high quality desert: roadless areas and vascular plant diversity. Our justification for using roadless areas, defined as all lands at least 1 km from a road (Ibisch et al., 2016), was that these areas are relatively unfragmented by human activities that tend to degrade environments. While roadless is not an exact measure of environmental integrity, roads are one of the most destructive human activities and are known to degrade biodiversity, increase invasive species, and provide easy access for humans to further modify the environment (Selva et al., 2015). Our justification for using vascular plant diversity begins with the fact that global biodiversity data on fine scales are not generally available for most taxa, including taxa with high biodiversity (e.g., arthropods). However, vascular plant diversity is, in general, strongly correlated with overall biodiversity in terrestrial systems (Brunbjerg et al., 2018), and so we used vascular plant species richness as an indicator of overall biodiversity.

For future risks, we assumed that wind and solar are the main energy systems that could rapidly expand into desert regions. Most traditional energy sources (e.g., oil and gas, hydropower) in desert areas are presumably already in production and have their associated land use impacts in place. We assumed other sources of energy besides wind and solar (e.g., geothermal) were either too small a scale or localized to be of significant global impact on these environments. Recent trends in wind and solar deployment support this assumption (McClung et al., 2019).

We identified desert areas using ecoregions as defined by Dinerstein et al. (2017). We excluded polar deserts (e.g., Antarctica) from our analysis because presumably they are too distant from most population centers to be cost effective renewable energy production areas. Using ArcGIS Desktop (ESRI, 2020), we clipped layers for potential wind resources (Technical University of Denmark, 2021), potential solar resources (Solargis, 2021), roadless areas (Ibisch et al., 2016), and vascular plant diversity (Kier et al., 2005) to our desert boundaries. The wind and solar resources layers came from the Global Wind Atlas 3.0 and Solar Wind Atlas 2.0, respectively. These free, web-based applications are developed and owned by the Technical University of Denmark (wind) and Solargis (solar) and developed utilizing data provided by Vortex (wind) and Solargis (solar), with funding provided by the Energy Sector Management Assistance Program.

We identified areas of economically viable wind and solar resources by using the extract by mask tool in ArcMap to create raster datasets with values above 5.8 m/s (at 100-m) for wind (U.S. Department of Energy, 2008) and 6.5 kWh/m² (DNI) for solar (National Renewable Energy Laboratory, 2012). We then used the extract by mask tool once again to find the regions of these energy raster datasets that overlapped with desert roadless areas and desert areas in four categories of plant diversity. These four categories represented 0–25, 25–50, 50–75, and 75–100% of the total number of plant species found in deserts, which ranged from 0 to 6,300 plant species. Once these energy raster datasets



were extracted by conservation category (i.e., roadless areas or four categories of plant diversity), their values were converted to integers so that we could use the zonal histogram tool to calculate the number of cells for each conservation category on each continent. This number of cells was then multiplied by the cell area (250 m^2) and summed to get total areas for each conservation category on each continent. We then calculated the proportion of total global desert area and the proportion of the total global conservation category occupied by each energy type on each continent by dividing the area for each of these categories by the total global area of deserts and the total global area of each conservation category, respectively.

RESULTS

As expected, many desert regions have abundant wind and solar resources (Figures 1A, 2A). Interestingly, the southern hemisphere deserts tend to have higher solar potential while the northern hemisphere deserts in Africa and Asia have the windiest regions. Perhaps surprisingly, the vast Sahara Desert has more high wind than high solar resource areas.

Most of the desert areas of the world remain roadless (defined as lands more than 1 km from a road, Ibisch et al., 2016; Table 1) and, therefore, relatively unfragmented. While deserts are sometimes known for their high biodiversity, only a small proportion of desert areas contain this high diversity. In total,

only 0.4% of desert areas occupy the highest 75% of percent plant species richness while almost 90% of desert lands contain the lowest 25% of plant diversity (Table 1). Therefore, plant species richness is highly concentrated in small regions of the biome. Even the top 50% areas of plant diversity are limited to the Karoo Desert of southern Africa, the Chihuahuan Desert of North America, and small isolated regions of East Africa, the Middle East, and South Asia. More than three-quarters of the roadless areas are regions that have the economically valuable wind resources while about one-quarter of the roadless areas contain regions of high solar potential (Table 2). However, almost all the best wind and solar areas fall in the low plant richness areas, which is not surprising considering the proportional dominance of the lowest 25% of richness areas (Table 2). Nonetheless, the highest 75% of plant diversity area (all in the Karoo Desert) has 56 and 79% of its area located in high resource wind and solar regions, respectively. While there is much overlap between high quality desert areas (both roadless and high diversity) and high renewable resource regions, there are also vast areas of lower quality desert available that have high solar and wind potential (Figures 1B,C, 2B,C).

There is continental variation in desert resources and potential impacts, with Africa and Asia having most roadless land at risk from wind development (Supplementary Table 1), representing about two-thirds of such areas. Australia and Africa have the greatest amount of solar potential areas that overlap with roadless

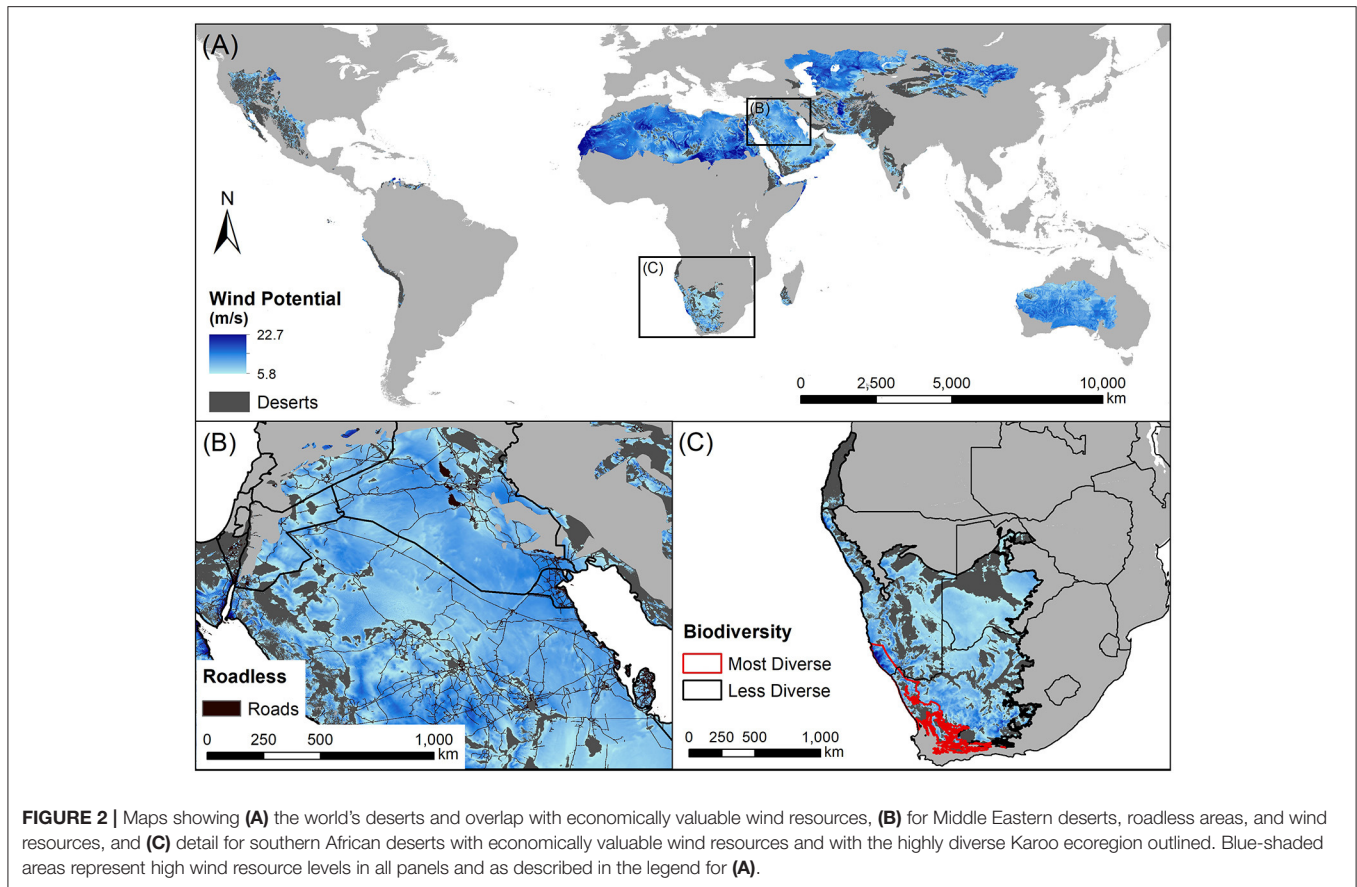


TABLE 1 | Total area (km²) and proportion of deserts that fall into the two methods of assessing conservation value: roadless areas and vascular plant diversity categories.

	Roadless	Plant diversity			
		0–25%	25–50%	50–75%	75–100%
Area (km ²)	22,048,667	22,133,601	1,995,558	658,071	94,523
Proportion	0.886	0.889	0.080	0.026	0.004

areas. For higher plant diversity areas (>50% of species richness), most of which are found in Africa, Asia, and North America, no continent stands out as at disproportional risk from either wind or solar (Figures 1, 2, Supplementary Table 1) except for the >75% plant diversity region of southern Africa which is almost entirely overlapping with high solar and/or wind resources (Figures 1C, 2C).

The specific regions we present in detail show the challenges and possibilities of wind and solar development. First, the deserts of southern Africa contain the highest diversity desert, but the high diversity region is mostly limited to the Karoo ecoregion, while other areas of the region have much lower diversity (Figure 1C). If the Karoo desert can be avoided, there are ample wind and solar resources elsewhere that could supply the regional human population with clean energy without impacting this

biodiversity hotspot (Figures 1C, 2C). The sunniest portions of these deserts are actually outside the Karoo (mostly north and west of the biodiversity hotspot), so it would probably be most cost effective to site solar arrays outside of the most ecologically valuable areas.

Similarly, the North American Deserts (Chihuahuan, Sonoran, Great Basin, and Mojave) are heavily fragmented in the northeastern and far west regions, while virtually all the areas south of the U.S. border in Mexico and to a lesser extent, northwestern parts of the U.S. area remain intact. Concentrating wind and solar development in currently developed areas could spare the most ecologically intact regions (Figure 1A).

The Middle Eastern desert is another region with abundant wind resources overlapping large areas of unfragmented desert. In general, fragmentation is limited to lands near cities and oil producing regions, which also tend to be some of the best wind resource areas (Figure 2B). In particular, Kuwait, Qatar, eastern Iraq, and coastal Saudi Arabia (Persian Gulf side) have significant fragmentation but could also support economically viable wind production.

DISCUSSION

Our analysis shows that deserts contain a large amount of unfragmented land and that a large proportion of it could be at risk for alternative energy development. The high biodiversity

TABLE 2 | Total area, proportion of total global desert area, and proportion of total desert conservation category area that contain economically viable wind and solar resources for each desert conservation category.

		Wind			Solar		
		Area (km ²)	Prop. global desert	Prop. desert conservation category	Area (km ²)	Prop. total desert	Prop. desert conservation category
Plant diversity	Roadless	17,390,685	0.675	0.789	6,079,894	0.244	0.276
	0–25%	16,789,952	0.675	0.759	5,158,555	0.207	0.233
	25–50%	416,635	0.017	0.209	496,667	0.020	0.249
	50–75%	131,010	0.005	0.199	350,244	0.014	0.532
	75–100%	52,838	0.002	0.559	74,392	0.003	0.787

desert areas are very small but have a large amount of overlap with high resource wind and solar energy regions. Fortunately, the overlap areas of high wind and solar resources with high biodiversity represent only a small portion of good potential renewable energy resources. Therefore, preventing energy development impacts on the most biological valuable regions will be relatively simple and practical compared to preventing impacts to the larger (gross and proportional) roadless areas. Nevertheless, we urge governments, energy industries, and private conservation groups to utilize our analysis to plan future alternative energy development. It seems almost certain that solar and wind energy production will continue to grow into the near and midterm future (Moriarty and Honnery, 2019), a process that is probably necessary to meet the mid-twenty-first century climate goals set forth by the U.N. to prevent more than 1.5°C warming (Fawzy et al., 2020). So, the question is probably not, will it happen, but where will it happen?

A good example from our analysis is the desert regions of Africa, which are largely roadless and contain some of the highest plant richness areas of deserts in the world (southern Africa) but could easily see rapid renewable energy development. To meet human development needs, the African continent generally needs a massive upgrade in energy production (Aliyu et al., 2018; Ouedraogo, 2019). North Africa has also been discussed as a likely place to generate renewable energy to provide parts of Europe and help that region decarbonize (Trieb et al., 2012). That puts the African deserts, which up until now have been somewhat immune to intensive development, at great future risk. Nonetheless, there are considerable areas of African deserts that are already impacted by human activity and/or relatively low diversity areas that could be utilized without damaging more ecologically sensitive regions. Furthermore, small areas of high-quality renewable energy production can supply a large piece of the vast energy needs of region (Trieb et al., 2012), supporting the argument that concentrating development in the relatively small areas already heavily impacted would be practical.

Even though quality desert habitat is at risk from increasing energy development, there are likely ways to mitigate the damage by using existing infrastructure. For instance, the U.S. portion of the Chihuahuan Desert is about one-third heavily impacted by development (energy, urban, and agriculture) and about two-thirds ecologically intact

(McClung and Moran, 2018; McClung et al., 2019). If the heavily developed portion, mostly now impacted by the oil and gas industry, was utilized for wind and solar, wider impacts to the ecosystem could be minimized. Considering that much of the oil and gas infrastructure (e.g., roads and powerlines) is also useful for other energy types, it could also be cost effective to utilize currently developed areas while sparing higher quality habitat. This recommendation would be a way to limit further ecosystem services loss for the region (Jordaan et al., 2021) and maintain an ecologically well-functioning landscape. Furthermore, restoration of lands on defunct infrastructure (e.g., inactive oil and gas wells) in select regions could be an effective mitigation strategy to further strengthen connectivity on high quality regions while energy development continues or expands in currently heavily impacted areas (McClung and Moran, 2018; Haden Chomphosy et al., 2021; Jordaan et al., 2021).

In the North American example (Figure 1B), there is a stark difference between the U.S. side of the border that has intense development and the Mexican side of the border which is largely intact. While encouraging development on the U.S. would limit further damage to this desert region, it also illustrates potential inequity between communities on both sides of the border who have a right to clean power. Creative development plans, such as cost and power sharing agreements between the U.S. and Mexico should be considered so that clean energy and environmental protection benefits are available to all people of the ecoregion.

The Middle East is another intriguing example. Because of the abundant oil and gas deposits, the region produces, either directly or indirectly, and large proportion of the world's greenhouse gases. Some authors have suggested that this region could produce and export vast quantities of renewable resources (Aslani et al., 2012), and with the strong history or energy production, would have the infrastructure and knowledge to make the transition profitably. Our analysis shows that the existing population centers and petroleum producing landscapes are also ideal for renewable energy production. This strategy would allow future energy development to reduce the region's carbon footprint while sparing many of the unfragmented deserts that characterize the area.

While this paper provides a global view of desert energy resources and risks, our examples above demonstrate the need for region-specific plans. Each desert area of the world contains

unique ecological, biological, and cultural interactions that make generalized recommendations difficult. Detailed local plans, such as the ones that have been produced in some regions (e.g., southern California, U.S. Bureau of Land Management, 2016), will need to be developed in other desert landscapes targeted for development if energy needs of the world (i.e., “affordable, reliable, sustainable, and modern energy for all,” United Nations, 2015) can be met while protecting unique irreplaceable resources.

Deserts remain one of more intact biomes on Earth, and while often considered as less desirable, low productivity landscapes, in reality they contain myriad unique ecosystems. While the impacts of grazing and traditional energy development (i.e., oil and gas) have impacted some areas (Moran et al., 2017; McClung et al., 2019) and defaunation remains an issue (Durant et al., 2014), deserts have largely been spared the drastic physical transformation of other habitats (e.g., conversion of grasslands to intensive agricultural landscapes; Bardgett et al., 2021). With the rapidly expanding renewable energy industry focusing on solar and wind, two resources that are abundant in desert regions, the status quo is not guaranteed. With careful planning though, our analysis shows that it would be possible to develop renewable energy resources that will help address climate change but, at the same time, not cause irreparable harm to these unique environments.

CONCLUSION

There is no doubt that energy needs will increase throughout much of the world in the future and that non-carbon energy sources, both for new energy and to replace existing carbon intensive energy, will be necessary to prevent catastrophic climate change (United Nations, 2015). These changes will

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- put many ecologically valuable lands, such as deserts, at risk, including those that have, to date, been spared the most intense development patterns. Our analysis suggests that it is possible to provide energy needs to the world and perhaps avoid major disruptions of remaining intact and highly functional ecosystems. It will take planning, but it is planning that needs to happen now while we are in the early phase of renewable energy adoption across the world.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

Both authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/frsus.2022.900468/full#supplementary-material>

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