Supplementary Materials for

# Renewable Energy on American Indian Land

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# Materials and Methods

This supplement provides details on sources and construction of data used in the analysis. We also provide an extended discussion of the methods and assumptions for our regression analysis, for the forecast scenarios, and other calculations found in the manuscript. Finally, we provide additional historical and legal information regarding the barriers highlighted in the discussion section of the manuscript.

## 1. Data Description

The main data characterize wind and solar endowments, utility-scale wind and solar facilities, land designation and ownership, and income across American Indian reservations and lands.

### *1.1 Raw Wind and Solar Endowments*

Figures 1 and 4 utilize data on wind speeds and solar photovoltaics (PV). Wind speeds are calculated using data from the National Renewable Energy Laboratory (NREL) and solar PV potential data come from the Global Solar Atlas. Wind speeds greater than 6.5 m/s are considered viable (Center for Sustainable Systems, 2021). For both figures, the wind and solar endowments are calculated by taking the mean of 30 x 30m pixels on all reservation-area land, non-reservation land (including public land), and privately owned land in the Contiguous United States.

### *1.2 Potential Wind and Solar Capacity*

Figure 2 employs estimates of the "technical potential" for utility-scale wind and solar from the National Renewable Energy Laboratory (Milbrandt et al. 2018). These estimates represent achievable energy generation given average wind and solar conditions as well as "topographic limitations, environmental, and land use constraints" (p. v). For wind and solar, the measures exclude water areas, urban areas, and protected lands such as parks, wilderness and wildlife refuges. The wind measure excludes land with greater than 20% slope, and the solar measure excludes land with greater than 5% slope.

### *1.3 Incomes on American Indian Reservations*

Figure 2 employs data on incomes of self-identified American Indians across federally recognized reservations. These data are compiled from the 2018 American Community Survey and represent incomes per capita for individuals on reservations who identified American Indian as a single race.

*1.4 Wind and Solar Facilities*

Figures 3 and 4 utilize data on the location of commercial wind turbines in the contiguous United States. These data come from the US Wind Turbine Database (USWTDB). The database is maintained by the US Geological Survey (USGS), the Lawrence Berkeley National Laboratory (LBNL) within the Department of Energy (DOE), and the American Clean Power Association (ACP). The database was first released in 2018 and is updated quarterly. It documents the size, capacity, year built, associated wind farm, and coordinates of every utility-scale wind turbine. This study uses data from the January 2023 edition, which contains 72,669 turbine records, although some with missing identifiers are dropped, resulting in a sample of 65,422 turbines. Using the geospatial coordinates, we link each wind turbine to an associated Public Land Survey System (PLSS) township.

The locations of utility-scale solar installations in the contiguous US come from data from the US Energy Information Administration (EIA). These data come from EIA Form 860. All generators that are at least 1 MW in size and connected to the power grid submit Form 860 each year.[1] Our sample includes solar installations that began operation in 2001-2022. These data include the generator capacity and location. We observe the latitude and longitude of each generator and not the solar farm's footprint, however a typical solar farm needs only 5-10 acres of land per MW (Ong et al., 2013). The median solar farm size in our data is 2.7 MW with an implied footprint of 14-27 acres. For the 90$^{th}$ percentile in terms of project size (32.2 MW), the implied footprint is 161-322 acres.

*1.5 Land Ownership and Management*

Figures 1, 3 and 4 utilize data on reservation areas (reservations and tribal statistical areas) from US Census shapefiles. Figures 1 and 4 utilize data on publicly owned land from the PAD-US 2.1 Database (US Geological Survey Gap Analysis Project, 2020). We focus on public land owned by federal and state governments.

[1] These data therefore exclude rooftop solar panels, which are typically much smaller than 1 MW.

## 2. Regression Variables

Wind Turbine Indicator: The dependent variable in Figure 4 panel (a) is an indicator equal to 1 if the township had any utility-scale wind installations as of the end of 2022.

Wind Capacity: The dependent variable in Figure 4 panel (b) is the aggregate number of Megawatts (MW) from utility-scale wind installations as of the end of 2022.

Solar Facility Indicator: The dependent variable in Figure 4 panel (c) is an indicator equal to 1 if the township had any utility-scale solar installations that began operation in 2001-2022.

Solar Capacity: The dependent variable in Figure 4 panel (d) is the aggregate number of Megawatts (MW) from utility-scale solar installations that began operation in 2001-2022.

Raw Wind Endowment: We control for wind speed using a national map of the mean speed in 2012 at 80m (in meters/second) from NREL. We calculate the mean wind speed for each township.

Raw Solar Endowment: We control for solar potential using a measure of practical PV potential from the Global Solar Atlas. This measure has many inputs including latitude, direct normal irradiance, temperature, terrain, and atmospheric conditions, and its units are kilowatt hours per installed kilowatt peak (kWh/kWp). These data were constructed by Solargis as part of an initiative funded by the World Bank (ESMAP 2020).

Transmission Lines: We calculate the number of kilometers of transmission lines using a spatial file from the Homeland Infrastructure Foundation-Level Data (HIFLD) and includes transmission lines ranging from 69 to 765 kilovolts (kV). We use the 2017 version of these data as we expect it to be a less endogenous control than the 2021 version. We additionally calculate the distance from township centroids to the nearest transmission line in kilometers. For a township with transmission within its borders, this value is 0. High-voltage transmission is considered a line above 161 kV.

Land Ownership: We use the Protected Area Database (PAD-US) to determine how much land is publicly owned (US Geological Survey Gap Analysis Project, 2020). For these data we calculate the proportion of township land owned by the federal, state, and local government (e.g., parks, forest service, and wildlife refuge land). The majority of this land is owned by the federal government, especially in the Western US.

Slope and Terrain Ruggedness: We calculate slope and terrain ruggedness at the township level using 30x30-meter elevation data from the National Elevation Dataset produced by the USGS. High slope lands and rugged terrains may pose challenges to siting renewable energy.

Land Use: We use spatial data from the National Land Cover Database (NLCD) from 2001 (USGS, 2014) to determine land-use proportions within townships.[2] Categories include cropland, pastureland, grassland, shrub-land, developed land, forest, barren, water, and ice. Importantly, developed land has buildings and other infrastructure that may make hosting wind or solar equipment impossible for legal or technical reasons.

Airports: For the wind energy regressions, we include the number of airports within each township, which may place restrictions on where wind turbines can be placed. Airport coordinates come from the Federal Aviation Administration (FAA).

[2] We choose 2001 as the year of measurement because land use in 2001 is exogenous (pre-determined) with respect to wind and solar development taking place over 2001-2023.

**Table S1: Summary Statistics**

| | Full Sample | | | In States with Reservations | | |
|---|---|---|---|---|---|---|
| Statistic | Mean | Min | Max | Mean | Min | Max |
| Wind Installed Capacity (MW) | 1.398 | 0 | 1,501 | 1.039 | 0 | 1,501 |
| =1 if Any Turbines | 0.026 | 0 | 1 | 0.019 | 0 | 1 |
| Solar Installed Capacity (MW) | 0.637 | 0 | 1,049 | 0.780 | 0 | 1,049 |
| =1 if Any Solar Farm | 0.021 | 0 | 1 | 0.021 | 0 | 1 |
| Share Reservation | 0.033 | 0 | 1 | 0.044 | 0 | 1 |
| Share Public Land | 0.316 | 0 | 1 | 0.437 | 0 | 1 |
| Mean Wind Speed | 6.266 | 1.823 | 11.78 | 6.139 | 1.823 | 11.78 |
| Solar Potential (kWh/kWp) | 1,605 | 952.3 | 2,123 | 1,619 | 952.3 | 2,123 |
| Km Transmission (2017) | 7.147 | 0 | 195.1 | 5.952 | 0 | 195.1 |
| Dist. To 2017 Trans. Lines (km) | 11.27 | 0 | 117.5 | 14.14 | 0 | 117.5 |
| Km High Voltage Transmission | 3.094 | 0 | 174.5 | 3.155 | 0 | 174.5 |
| Airports | 0.118 | 0 | 5 | 0.093 | 0 | 5 |
| Share Developed | 0.047 | 0 | 1 | 0.032 | 0 | 1 |
| Share Barren | 0.012 | 0 | 1 | 0.020 | 0 | 1 |
| Share Forest | 0.215 | 0 | 1 | 0.205 | 0 | 1 |
| Share Shrubland | 0.244 | 0 | 1 | 0.346 | 0 | 1 |
| Share Grassland | 0.160 | 0 | 1 | 0.174 | 0 | 0.998 |
| Share Cropland | 0.189 | 0 | 1 | 0.138 | 0 | 1 |
| Share Pasture | 0.055 | 0 | 1 | 0.029 | 0 | 1 |
| Share Wetlands | 0.061 | 0 | 1 | 0.041 | 0 | 1 |
| Share Water | 0.016 | 0 | 1 | 0.015 | 0 | 1 |
| Slope | 2.215 | 0 | 33.48 | 2.930 | 0 | 33.48 |
| Terrain Ruggedness Index | 3.740 | 0 | 84.77 | 4.922 | 0 | 64.61 |

**Notes**: The full sample size of townships is N = 58,822. The sample size of townships in states with reservations is N = 33,170.

### 3. Regression Analysis of Wind and Solar Installed Capacity

Because the raw data on renewable energy investment are available in a disaggregated, georeferenced form, we must choose how to aggregate the data spatially prior to analysis. We must decide between using administrative units (e.g., counties, townships, census tracts, etc.) or imposing a spatial grid and conducting analysis of arbitrary sized cells within that grid. We choose to analyze townships because their size is uniform (at 6x6 square miles) as established by the Public Land Survey System (PLSS) of the United States. This uniformity makes coefficient interpretation intuitive and transparent. Township sizes are smaller than most Indian reservation areas, especially those in the western United States, and their sizes are predetermined, meaning we do not have to arbitrarily choose grid sizes.[3]

Using the variables in Table S1, we implement a cross-sectional analysis at the township level in which installed renewable energy capacity through 2022 is determined by raw endowments, transmission lines, and other factors. Because we focus on the comparison between on versus off reservation land, this estimation procedure differs from Evans et al. (2022), who use a sample of reservations to understand correlates of wind energy development across reservations (e.g., presence of casinos). Our regression equation is

$$(1)\ Capacity_{tc} = \delta_c + \beta(Prop.Reservation)_t + \mu(Prop.Public)_t + \delta X_t + u_{tc}\ ,$$

where "t" denotes township and "c" denotes county. Here capacity is a function of the proportion of reservation area land in a township, the proportion of public land, and the suite of covariates described above. The omitted category is the proportion of private, off-reservation land. The notation $\delta_c$ indicates that we include county fixed effects, implying the key coefficient of interest, $\beta$, is identified from within-county variation in the amount of reservation area land. Including county fixed effects controls for unobserved variation in topography, endowments, and distance to infrastructure and electricity markets. Standard errors are clustered at the county level.

When can we interpret $\beta$ as a causal effect of reservation status on installed capacity? The key concern is omitted variables. If the covariates and county fixed effects fail to account for factors that are systematically correlated with reservation area land, and that also determine energy development attractiveness, then our estimate of $\beta$ will embed some of this effect. We think this is unlikely given the rich set of covariates included in the regression estimates.

Table S2 shows regression results for wind capacity. The dependent variable in Columns 1-3 is an indicator for whether a wind farm is present in a township (as shown in Figure 4, panel (a)). The dependent variable in Columns 4- 6 is installed capacity, expressed in MW (as shown in Figure 4, panel (b)). Only Columns 2,3,5,6 include controls for access to transmission lines. We show results with and without the transmission line controls to account for the possibility that

[3] Many of the original 13 colonies do not use the PLSS system but townships are used in all states with significant American Indian populations on reservations. See https://www.sidwellco.com/company/resources/public-land-survey-system/.

transmission accessibility is endogenous to the share of reservation land and hence a possible channel through which reservation land affects installed capacity. All specifications include the full sample of townships, including those in states without reservation/tribal statistical area land.

Townships with a greater share of reservation land are significantly less likely to host wind farms, especially large ones, even after controlling for endowments, transmission lines, land use, and infrastructure. The Column 1 coefficient indicates that, an increase in the share of reservation land from 0 to 1 reduces the probability of any wind farming by 0.012 when compared to off-reservation private land in the same county. This is a 46% decrease relative to the mean of 0.026. The Column 4 coefficient indicates that an increase in the share of reservation land from 0 to 1 reduces the energy capacity of wind farming by about 0.632 MW, which is 45% relative to the mean of 1.40 when compared to off-reservation private land in the same county.

Table S3 shows regression results for solar capacity. The specifications mimic those in Table S2 except that here we control for average solar photovoltaic potential rather than wind potential. The Column 1 coefficient Table S3 indicates that an increase in the share of reservation land from 0 to 1 reduces the probability of any solar farming by 0.023 when compared to off-reservation private land in the same county. This is a 110% decrease relative to the mean of 0.021. As with wind, the negative effect of the share of reservation land is statistically indistinguishable from the negative effect of other public lands. The Column 4 coefficient indicates that an increase in the share of reservation land from 0 to 1 reduces the energy capacity of solar farming by about 0.762 MW, which is 120% relative to the mean of 0.637 when compared to off-reservation private land in the same county.

The findings in Tables S2 and S3 are mostly robust to other specifications and subsamples that we do not show here. The effect of share reservation land is similar when we replace county fixed effects with state fixed effects and doing so makes the solar radiation coefficient positive and statistically significant.[4] Dropping observations in states without Indian reservation land does not affect the pattern of results. Furthermore, the findings look qualitatively similar when excluding observations from Oklahoma, which is comprised primarily of tribal statistical areas rather than federal reservations, and which have been in jurisdictional flux (see Johnston and Parker 2022).

[4] Including county fixed effects forces comparisons between townships in the same county that could make the results sensitive to possible spillover effects of one township's activity on neighboring townships. The fact the findings are the similar without county fixed effects suggests that spillovers are not driving the findings.

## Table S2: Predictors of Installed Wind Capacity

| | *Dependent variable:* | | | | | |
|---|---|---|---|---|---|---|
| | =1 if Wind Turbine | | | MW Wind | | |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Share Reservation | -0.012*** | -0.009** | -0.008** | -0.632** | -0.413* | -0.396* |
| | (0.004) | (0.004) | (0.004) | (0.265) | (0.235) | (0.231) |
| Share Public Land | -0.011*** | -0.008** | -0.008** | -1.005* | -0.790 | -0.779 |
| | (0.003) | (0.003) | (0.003) | (0.528) | (0.491) | (0.485) |
| Mean Wind Speed | 0.020*** | 0.021*** | 0.021*** | 2.016*** | 2.044*** | 2.045*** |
| | (0.003) | (0.003) | (0.003) | (0.723) | (0.725) | (0.726) |
| IHS(Km Transm) | | 0.006*** | 0.005*** | | 0.422*** | 0.409*** |
| | | (0.001) | (0.001) | | (0.090) | (0.085) |
| Dist to Trans. (Km) | | | -0.0001 | | | -0.003 |
| | | | (0.0001) | | | (0.005) |
| Log(Land Area) | 0.003*** | 0.001* | 0.001* | 0.204*** | 0.073 | 0.076 |
| | (0.001) | (0.001) | (0.001) | (0.079) | (0.062) | (0.063) |
| Airports | -0.005** | -0.006*** | -0.006*** | -0.576*** | -0.650*** | -0.649*** |
| | (0.002) | (0.002) | (0.002) | (0.128) | (0.131) | (0.131) |
| Share Developed | 0.011 | -0.010 | -0.010 | 0.598 | -0.943 | -0.947 |
| | (0.015) | (0.015) | (0.015) | (1.100) | (1.167) | (1.168) |
| Share Barren | 0.029* | 0.030* | 0.032** | 3.962*** | 4.052*** | 4.098*** |
| | (0.017) | (0.016) | (0.016) | (1.397) | (1.365) | (1.372) |
| Share Forest | -0.010 | -0.011 | -0.011 | -0.132 | -0.182 | -0.180 |
| | (0.014) | (0.014) | (0.014) | (1.139) | (1.138) | (1.138) |
| Share Shrubland | 0.022 | 0.020 | 0.019 | 2.383** | 2.167* | 2.162* |
| | (0.015) | (0.015) | (0.015) | (1.134) | (1.125) | (1.124) |
| Share Grassland | 0.038** | 0.034** | 0.034** | 3.623*** | 3.341** | 3.332** |
| | (0.017) | (0.017) | (0.017) | (1.367) | (1.351) | (1.351) |
| Share Cropland | 0.056*** | 0.051*** | 0.050*** | 4.640*** | 4.229** | 4.213** |
| | (0.018) | (0.017) | (0.017) | (1.642) | (1.671) | (1.678) |
| Share Pasture | -0.009 | -0.019 | -0.019 | -0.410 | -1.160 | -1.169 |
| | (0.016) | (0.016) | (0.016) | (1.192) | (1.213) | (1.214) |
| Share Wetlands | -0.001 | -0.004 | -0.005 | 0.659 | 0.428 | 0.413 |
| | (0.013) | (0.013) | (0.013) | (0.838) | (0.830) | (0.828) |
| Land Slope | -0.009*** | -0.008*** | -0.008*** | -1.160** | -1.083** | -1.074** |
| | (0.003) | (0.002) | (0.002) | (0.476) | (0.455) | (0.450) |
| Terrain Ruggedness Index | 0.005*** | 0.004*** | 0.004*** | 0.588** | 0.559** | 0.554** |
| | (0.002) | (0.001) | (0.001) | (0.257) | (0.247) | (0.244) |
| Observations | 58,822 | 58,822 | 58,822 | 58,822 | 58,822 | 58,822 |
| $R^2$ | 0.458 | 0.460 | 0.460 | 0.310 | 0.311 | 0.311 |

*Notes: Standard errors (clustered by county) in parentheses. Model includes county fixed effects.* *p<0.1, **p<0.05, ***p<0.01

## Table S3: Predictors of Installed Solar Capacity

| | *Dependent variable:* | | | | | |
|---|---|---|---|---|---|---|
| | =1 if Solar Farm | | | MW Solar | | |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Share Reservation | $-0.023^{***}$ | $-0.020^{***}$ | $-0.021^{***}$ | $-0.762^{**}$ | $-0.519^{*}$ | $-0.517^{*}$ |
| | (0.007) | (0.006) | (0.006) | (0.310) | (0.296) | (0.294) |
| Share Public Land | $-0.026^{***}$ | $-0.023^{***}$ | $-0.023^{***}$ | $-1.121^{*}$ | -0.873 | -0.871 |
| | (0.005) | (0.005) | (0.005) | (0.618) | (0.593) | (0.597) |
| Mean Global Horizontal Irradiance | $-0.0001^{***}$ | $-0.0001^{***}$ | $-0.0001^{***}$ | 0.0004 | 0.001 | 0.001 |
| | (0.00004) | (0.00004) | (0.00004) | (0.005) | (0.005) | (0.005) |
| IHS(Km Transmission) | | $0.006^{***}$ | $0.006^{***}$ | | $0.463^{***}$ | $0.461^{***}$ |
| | | (0.001) | (0.001) | | (0.099) | (0.101) |
| Distance to Trans. (Km) | | | 0.00002 | | | -0.0005 |
| | | | (0.0001) | | | (0.004) |
| Log(Land Area) | $0.008^{***}$ | $0.006^{***}$ | $0.006^{***}$ | $0.194^{***}$ | 0.047 | 0.047 |
| | (0.001) | (0.001) | (0.001) | (0.059) | (0.068) | (0.069) |
| Share Developed | $0.201^{***}$ | $0.179^{***}$ | $0.179^{***}$ | $-3.483^{**}$ | $-5.220^{***}$ | $-5.220^{***}$ |
| | (0.030) | (0.029) | (0.029) | (1.606) | (1.766) | (1.765) |
| Share Barren | $-0.046^{**}$ | $-0.045^{**}$ | $-0.046^{**}$ | 0.194 | 0.245 | 0.253 |
| | (0.020) | (0.019) | (0.019) | (1.942) | (1.913) | (1.927) |
| Share Forest | $-0.033^{***}$ | $-0.033^{***}$ | $-0.033^{***}$ | 0.557 | 0.533 | 0.533 |
| | (0.012) | (0.011) | (0.011) | (0.789) | (0.776) | (0.776) |
| Share Shrubland | $-0.051^{***}$ | $-0.054^{***}$ | $-0.054^{***}$ | -0.316 | -0.575 | -0.575 |
| | (0.014) | (0.014) | (0.014) | (1.075) | (1.045) | (1.044) |
| Share Grassland | $-0.031^{**}$ | $-0.035^{***}$ | $-0.035^{***}$ | -0.794 | -1.111 | -1.112 |
| | (0.013) | (0.013) | (0.013) | (0.908) | (0.911) | (0.911) |
| Share Cropland | 0.018 | 0.012 | 0.012 | 0.488 | 0.023 | 0.021 |
| | (0.014) | (0.014) | (0.014) | (0.913) | (0.928) | (0.929) |
| Share Pasture | 0.022 | 0.011 | 0.011 | 3.531 | 2.658 | 2.657 |
| | (0.022) | (0.022) | (0.022) | (2.525) | (2.501) | (2.505) |
| Share Wetlands | -0.003 | -0.007 | -0.006 | $-1.185^{*}$ | $-1.446^{**}$ | $-1.448^{**}$ |
| | (0.012) | (0.012) | (0.012) | (0.668) | (0.664) | (0.664) |
| Land Slope | -0.005 | -0.004 | -0.004 | 0.035 | 0.141 | 0.142 |
| | (0.003) | (0.003) | (0.003) | (0.429) | (0.450) | (0.450) |
| Terrain Ruggedness Index | 0.0004 | -0.0001 | -0.0001 | -0.219 | -0.259 | -0.260 |
| | (0.002) | (0.002) | (0.002) | (0.278) | (0.290) | (0.290) |
| Observations | 58,822 | 58,822 | 58,822 | 58,822 | 58,822 | 58,822 |
| $R^2$ | 0.297 | 0.299 | 0.299 | 0.100 | 0.102 | 0.102 |

*Notes: Standard errors (clustered by county) in parentheses. Model includes county fixed effects.* $^{*}$p<0.1, $^{**}$p<0.05, $^{***}$p<0.01

4. **Forecasted Implications for Future Earnings**

To estimate potential forgone earnings, we use regression coefficients from Column 4 of Tables S2 and S3 (Model 1 in Figure 4, panels (b) and (d)) that estimate the off versus on reservation disparity in current installed capacity and multiply it by the share of reservation land within each township.[5] Second, we multiply the resulting differentials by the forecasted rate of wind and solar growth from 2022 through 2050 to estimate foregone utility-scale installed capacity (in MWs) if current disparities persist.[6] Third, we multiply the foregone electricity generation capacity estimates by estimates of the land lease and tax payments per MW to arrive at an estimate of foregone payments. Fourth, we discount the stream of foregone payments over time and then express the foregone earnings in present value terms.[7]

"REF" refers to the reference scenario. "E+" refers to high electrification. "E-" refers to low electrification. "E- B+" refers to a high-biomass scenario. "E+ RE-" refers to high electrification and low renewable supply. "E +RE+" refers high electrification and 100% renewable supply.[8]

<u>Wind lease payments</u>: We assume annual lease payments to landowners for wind farms will be $6,686 per MW. This number results from taking total annual lease payments for US wind projects in 2019 ($706 million) and dividing it by total installed wind capacity as of 2019 (105,591 MW). The estimate of total payments to landowners comes from the 2019 Annual Report for the American Wind Energy Association, which was the last report to separate wind from solar leases (AWEA, 2020).

[5] For example, for a township entirely covered by a reservation, the wind disparity would be equal to 1 * 0.632 = 0.632 MW. For a township only half covered the disparity would be 0.5 * 0.632 = 0.316 MW. These individual disparities are then summed over the entirety of the sample to get the total capacity disparity.

[6] That is, if the amount of total capacity in a future year is projected to be 20% higher, the disparity from step one would be 20 percent larger.

[7] We assume there is ample land off reservations to supply electricity generation under all scenarios, ruling out a large-scale shift to reservations due to a lack of substitute land.

[8] The REF scenario is described as: "Based on US EIA, *Annual Energy Outlook 2019* (Reference case, no new policies), no greenhouse gas emission constraints imposed, same (low) projected oil and gas prices as for net-zero pathways. The E+ scenario is described as: "Nearly full electrification of transport and buildings by 2050, no land-use change for biomass supply allowed, and Few other constraints on energy supply options." The E- scenario is described as "less-rapid electrification of transport and buildings, no land-use change for biomass supply allowed, few other constraints on energy supply options." The E+RE+ scenario is the same as the E+ scenario and "no new nuclear power construction allowed, existing plants retired, no underground storage of CO2 allowed."

Solar lease payments: Solar lease payments are typically made on a per acre basis with annual payments per acre ranging from $250 to $2500 depending on local land availability, site location relative to transmission lines, site conditions like slope, and the number of acres leased (Wolpert 2021). We assume an intermediate value of $1000 per acre. A typical solar farm employs 5-10 acres of land per MW (Ong et al. 2013). By assuming 7.5 acres leased per MW, we arrive at an annual payment of $7,500 per MW.

Tax payments: Local governments receive tax payments from wind and solar farms primarily in the form of annual property taxes, but both the level and type of these payments vary widely across the US.[9] To estimate average tax payments, we take the total state and local tax payments by US wind developers in 2019 ($912 million) based on AWEA (2020) and divide it by the total installed wind capacity in MW in 2019 (105,591 MW). We apply the resulting estimate, which is $8,637 per MW, to both wind and solar in our forecasts.

Decarbonization scenarios: We draw on six scenarios from the Princeton Net-Zero America report (Larson et al. 2021). Each scenario projects total installed capacity for utility-scale solar and onshore wind at 5-year intervals from 2020 through 2050. These projections imply a growth rate for each type for each 5-year window, which we use for our forecasts. Importantly for our purposes, the forecasts vary in their implications for the amount of solar and onshore wind that will be employed in the future.

Discount rate: We use a real discount rate of 3 percent for all calculations. This is the discount rate employed by Hsiang et al. (2017).

These back-of-the-envelope calculations might understate or overstate the earnings foregone under the decarbonized electricity scenarios. First, the estimates do not consider wage and employment benefits that might accrue to tribal members from renewable construction and maintenance. Second, the estimates also do not consider multiplier benefits to other reservation activity that could accrue from spending of land lease and tax earnings. Third, the estimates assume current leasing payment levels will persist over the next 28 years, and that those payments

[9] See Brunner et al. (2021) Appendix B for a detailed description of how different US states tax wind installations.

are invariant across the different scenarios. In fact, a variety of factors including increasingly scarce land and changes in technology and transmission infrastructure could cause payments to change over time.

Another issue is that tribal governments may not have equivalent leverage to exact taxes from reservation renewable development when it is on fee simple lands (Crepelle 2020). Tribes and states might enter into tax sharing agreements similar to that on Fort Berthold Indian reservation through which oil extraction taxes are split between the Three Affiliated Tribes and the state of North Dakota wherever the development takes place within the reservation (Leonard and Parker 2021). If tax revenues are shared with state or county jurisdictions, then our estimates may overstate benefits to tribal members.

Note that we also use the data just described to provide a preliminary assessment of the "potential for renewable energy to alleviate poverty" beneath Figure 1 in the main text. To arrive at the lower bound calculation of $497 million, we first multiply the reservation area's proportion of the nation's (lower 48-states) renewable energy potential – which is 8.8% for wind and 5% for solar (from Milbrandt et al. 2018) – by the baseline reference scenario expansion of renewables by year 2050 (from Larson et al. 2021, Table 42) – to arrive at a projected amount of wind and solar on reservations in 2050. These numbers are 307.4 GW x 0.088 = 2.7 GW (or 27000 MW) for wind and 101.4 GW x 0.05 = 0.5 GW (or 5000 MW) for solar. Second, we multiply these calculations by annual lease and tax payment estimates to arrive at 27000 x $6,686 = $181 million for wind leases, 27000 x $8,637 = $234 million for wind taxes, 5000 x $7,500 = $38 million for solar leases, and 5000 x $8,637 = $43 million for solar taxes. Aggregating these figures yields $491 million.

To arrive at the upper bound calculation of $4.9 billion, we use the same procedure based on projected 2050 energy portfolios in the most aggressive net zero simulation (Larson et al. 2021, Table 90). Here we substitute 2186.5 GW for 307.4 in the case of wind, and 2454.6 GW for 101.4 in the case of solar and otherwise employ the same numbers in the calculations.

## 5. Additional Statistical Tests

### *5.1 Difference in Distribution of Raw Wind and Solar Endowments*

Figure 1 shows the distribution of raw endowments across reservation, all non-reservation lands, and non-reservation lands that are privately owned. We employ Kolmogorov-Smirnov tests to determine if these distributions are statistically different. Table S4 below summarizes the results. We conclude the distributions are statistically distinct at p<0.01.

**Table S4**

**Energy Potential Tests Statistics from Kolmogorov-Smirnov Test**

| Comparison Distribution | Wind | Solar |
|---|---|---|
| Non-Reservations | 0.0681*** | 0.169*** |
| Private Land | 0.0589*** | 0.186*** |

**Notes:** The Kolmogorov-Smirnov test is implemented to identify equivalence across distributions of wind and solar potential between on Reservations and the comparison groups from Figure 1. The *** across all specifications indicates rejecting the null of equivalent distributions at the p<0.01 level, implying different wind and solar potential distributions on Reservation land.

### *5.2 Comparison of Endowments for Tribes with and without Casinos*

The section on "Potential for Renewable Energy to Alleviate Poverty" references comparisons of mean raw endowments for reservation areas with and without casinos. The comparisons are shown below. From them, we conclude that reservations without casinos are better endowed with wind and solar endowments on a per-capita basis.

**Table S5**
**Mean Per Capita Renewable Endowments on Reservations**

| | With a Casino (N = 198) | Without a Casino (N = 86) | t-stat for diff., equal variance | t-stat for diff., unequal variance |
|---|---|---|---|---|
| Utility Scale Solar, kWh per capita | 5,276 | 18,059 | 2.34** | 1.57 |
| Utility Scale Wind, kWh per capita | 1,277 | 4,890 | 2.62*** | 1.75* |

**Notes:** The number of observations is N = 198 reservations with at least one tribal gaming facility and N = 86 reservations with no gaming facilities. * p <0.1, **p<0.05, ***p<0.01 for 2-tailed t-tests. MW per capita refers to renewable energy "potential capacity" (in kilowatt hours) on the reservation and adjacent trust lands divided by the American Indian population in 2018. The t-stats assume equal and unequal variance.

**Data sources:** The gaming data come from Casino City's Gaming Directory, last accessed on March 1, 2022. The data set categorizes the following properties: Bingo Hall, Card Room, Casino Cruise, Commercial Casino, Dog Track, Dog Track Racino, Horse Track, Horse Track Racino, Indian Casino, and Off-Track Betting Facility. Our analysis focuses on the property defined as "Indian Casino." The measures of renewable energy come from the National Renewable Energy Laboratory's Tribal Energy Atlas, available at: https://maps.nrel.gov/tribal-energy-atlas/.

## 6. Supplemental Information to Support Discussion Section

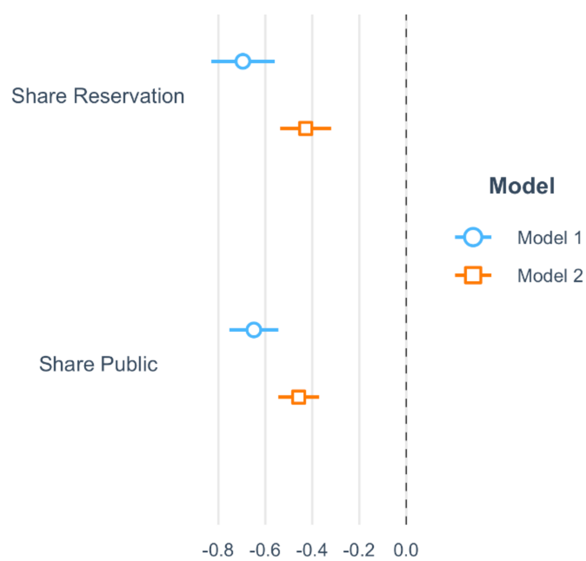
### *6.1 Foregone Earnings from Renewables Compared to Casino Earnings*

Data on tribal casino profits are proprietary but annual reports that provide data on revenue are available from the National Indian Gaming Commission at www.nigc.gov/commission/gaming-revenue-reports/. These data show that aggregate tribal gaming revenue was $34.6 billion in 2019 before dipping to $27.8 billion in 2020. The comparisons in the discussion section assume a profit margin of 10% of revenue. The net present value of income flow from 2021 to 2050 if tribal casinos earn a profit margin of 10% of revenue would be $\sum_{t=1}^{t=30} \frac{\$34b \times 0.1}{(1+r)^t}$ , where r is the discount rate. At discount rate of 0.03, the present value of casino profit is $67 billion.

### *6.2 Transmission Lines*

The manuscript indicates that townships comprised of all reservation area land had 70% fewer km of transmission lines (Model 1) and 43% fewer km of high voltage lines (Model 2) when compared to non-reservation townships as of 2021. Figure S1 summarizes the regression results from which these estimates are obtained.

**Figure S1: Coefficient Plots for Township Level Estimates of Transmission Density**




**Notes:** The coefficient estimates are shown on the horizontal axis along with point estimates and 95% confidence error bars. In Model 1, the outcome variable is km of all transmission lines. In Model 2, the outcome variable is km of high voltage transmission lines. Both models control for same variables listed in Tables S2 and S3 (with the exception of transmission lines and for both wind and solar endowments).

Further analysis indicates that eliminating the gap in transmission line density would increase the probability of wind (solar) development in a township comprised of all reservation land by 12% (14%) relative to the mean. We derive these results from interpretating the change in coefficients moving from Column 1 to Column 2 in Table S2, and from Column 1 to Column 2 in Table S3.

*6.3 Completion of Planned Projects on versus off Reservations*

Several tribes have signaled their desire to launch renewable projects, and evidence from planned projects suggests that tribal projects are subject to higher failure rates. We compare project failure rates using data on planned projects from Energy Information Administration (EIA) Form 860 for 2001-2022. Both operating generators and generators in the planning stage are supposed to submit this form every year, though these data likely capture only a subset of planned generators. Reservations have 1.9% of completed solar projects but 3.2% of solar projects that appear as planned by 2019 but are not in operation by 2022 (14 projects). For wind, we find similar failure rates on and off reservations. These results obviously do not account for the implicit failure rate of projects that are never planned because of expected failure.

*6.4 Trusteeship, Fractionation, and Regulations over Renewables*

Federal trusteeship has its origins in three US Supreme Court decisions penned by Chief Justice John Marshall. In 1823, he ruled the federal government holds title to Indian land, and in 1831 he likened Indian territories to "nations within a nation" but also stated that such areas were "domestic dependent nations." Although implying that tribes had retained internal powers to govern themselves, Marshall described the relationship between tribes and the United States as "that of a ward to his guardian." In a third decision, Marshall ruled that Indian lands are under federal, rather than state, jurisdiction.

During the Allotment Period, millions of acres of tribal land were allotted to Native Americans, but title was held in trust by the federal government. After 25 years or when the Indian agent deemed the allottee to be "competent and capable," the title could be released from trust and fully privatized as fee simple property. Some reservations were completely allotted and privatized, whereas other reservation lands were never allotted and remained held by tribes, rather than by individuals. Between these extremes are reservation lands that were allotted but not released from trusteeship, which we call allotted trust land. Figures S2 and S3 map land ownership on two Indian reservations – the Cheyenne River in South Dakota and Fort Berthold in North Dakota – to illustrate the ownership mosaics that dominate many reservations with valuable endowments of wind or solar. Approximately 80% of land on Indian reservations is held in trust compared to 15% in fee simple.

**Figure S2: Land Ownership on the Fort Berthold Reservation**

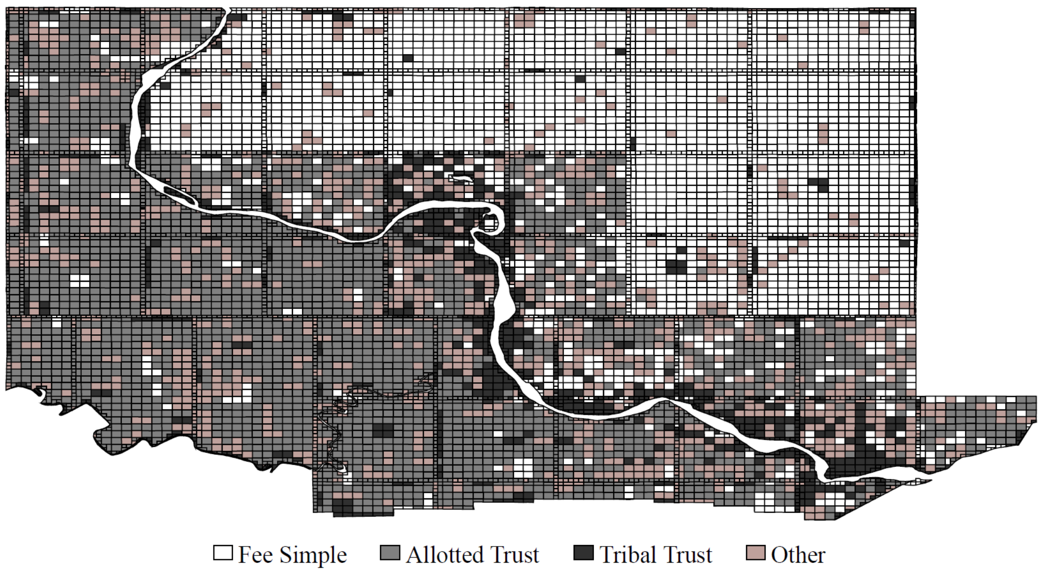
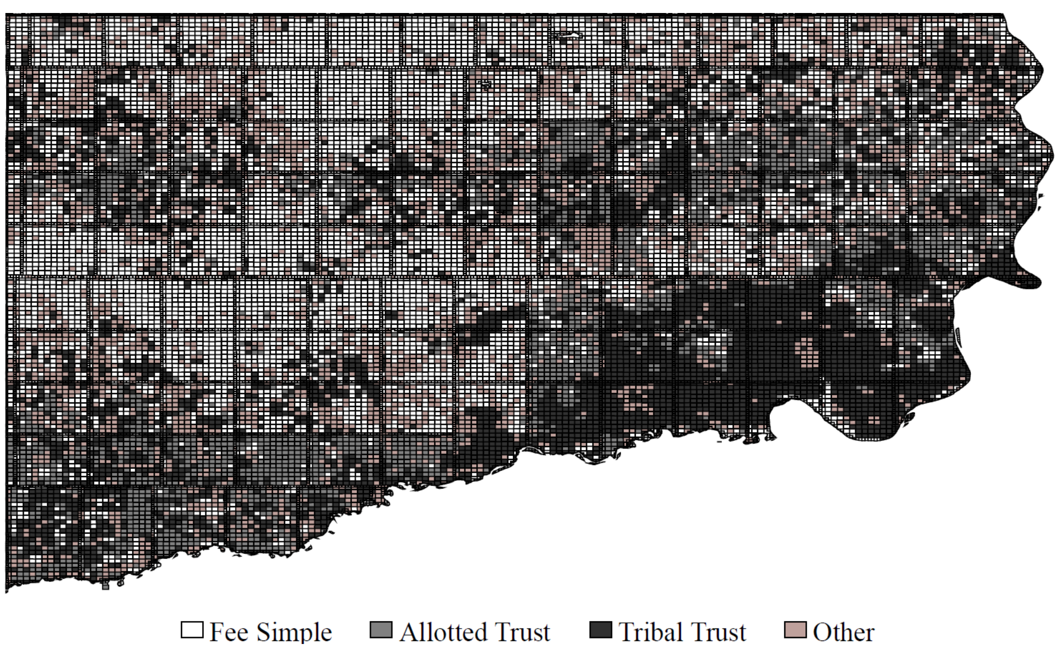



**Figure S3: Land Ownership on the Cheyenne River Reservation**



Tribal governments typically retain authority to regulate solar and wind farms within the reservation boundary, and they may create reservation-wide policies such as set-back requirements for wind turbines that apply to all ownership types. Proposed renewable projects on trust land are subject to approval by the BIA. BIA involvement typically triggers a National Environmental Policy Act (NEPA) review. NEPA reviews are also required on federal public lands and are known to delay and sometimes prevent development projects (Ravotti 2017). NEPA does not apply to fee simple parcels whether on or off reservations.

Although the federal government holds the underlying title in both cases and imposes the same regulatory oversight, only one entity (the tribe) has consolidated control over use rights. Hence, a wind or solar energy developer must go through trusteeship regulatory hurdles and negotiate with the tribe to implement a development project. For allotted trust land, a developer must negotiate with a large number of owners who have fractionated interests in parcels of reservation land. Allotted trust land was subdivided into 160, 80, and 40-acre parcels during 1887-1933 but, unlike fee simple land, was never privatized and released from trusteeship.

The Department of Interior's report also highlights the problem of fractionation. It states (2013, 7):

> Unless an individual or a tribe owns a controlling interest in a fractionated tract, they must seek and obtain approval from co-owners for any purpose, including leasing or economic development. When tracts have hundreds or thousands of co-owners, there is no practical way to obtain the required approvals for leases or other uses of such lands.

*6.5 Tribal Sovereignty and Rule of Law*

Uncertain legal conditions could reduce investments in transmission lines, solar panels, and wind turbines because much of the value of these investments are site-specific and sunk after installation. Sunk investments are exposed if a tribal government - or any government - makes ex-post changes in regulations, leasing terms, or tax rates leaving the outside investor with little recourse (see, e.g., Klein et al. 1978). The hypothesis that follows is that tribes will have difficulty attracting renewable development in light of sovereign authority to regulate, adjudicate, and tax.[10] Tribes could waive sovereign immunity from suit as they have often done in contracts with casino

[10] This is especially problematic if the renewable investors might be exposed to dual taxation from both the tribe and the state (see Crepelle 2020).

operating companies. Sovereign governments, however, cannot waive their inherent regulatory and taxing authority, meaning investors might remain wary of making sunk capital investments that could be regulated or taxed in the future. Tribes could borrow money and develop renewables on their own rather than contracting with a non-tribal developer. The problem is that tribes may have to pay a high interest rate. Loftus et al. (2022) find that tribal governments pay 22% to 87% higher borrowing costs than nontribal governments when issuing municipal bonds. This highlights the capital and contracting challenges of attracting or building renewable energy.

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