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Drivers and energy justice implications of renewable energy project siting in the United States

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Drivers and energy justice implications of renewable energy project siting in the United States

The rapid expansion of solar and wind energy projects is raising questions of energy justice. Some scholars argue that solar and wind project development could burden under-resourced communities with negative impacts such as environmental harm and reduced access to resources. Conversely, other scholars argue that project development could be a boon to under-resourced communities, providing local economic and cultural benefits. Here, we analyze the drivers of solar and wind project siting patterns in the United States and explore their potential energy justice implications. We find that siting patterns are driven primarily by technoeconomic factors, especially resource quality and access to open undeveloped spaces. These technoeconomic factors channel projects into sparsely populated rural areas and, to a lesser extent, areas with lower income levels. We avoid simplifying assumptions about the broad justice implications of these siting patterns and explore our results from multiple perspectives.

Keywords: solar; wind; siting; land use; energy justice

Introduction

Utility-scale solar and wind are vital components of efforts to decarbonize electric grids. Decarbonization studies envision solar and wind meeting more than 50% of electricity demand by 2050, primarily through utility-scale projects (DOE, 2021; IEA, 2021; Larson et al., 2020). Realizing this vision will require dedicating significant land area to solar and wind project development (Lopez et al., 2021; Ong et al., 2013; van de Ven et al., 2021). Solar and wind project siting has emerged as one of the key challenges to the large-scale deployment of these resources (Firestone et al., 2018; Kahn, 2000; Tegen et al., 2016; Vajjhala, 2006). Solar and wind project sites are constrained to a limited number of areas with economically-viable solar and wind resources and access to grid infrastructure (Outka, 2010; Vajjhala, 2006). Solar and wind project siting is further constrained by public opposition, public utility regulations, land use regulations, competition with existing land uses, and environmental constraints (Carley et al., 2020; Mai et al., 2021; Outka, 2010; Rand & Hoen, 2017; Zichella & Hladik, 2013).

More recently, social justice objectives have emerged as another potential constraint on project siting (Bailey & Darkal, 2018; S. Baker, 2021; Ottinger et al., 2014; Phadke, 2013). This trend is motivated, in part, by the historically inequitable siting patterns of fossil fuel plants and industrial facilities; rural, low-income, and other under-resourced communities bear disproportionate shares of the burdens of fossil fuel power plants (Sovacool & Dworkin, 2014). However, as we discuss further in the Literature Review, the impacts of solar and wind projects on project host communities are more ambiguous and contextual than those of fossil fuel projects.

Solar and wind project siting could play a key role in the growing clean energy justice agenda, broadly defined as a framework that fairly distributes the benefits and costs of energy systems and ensures fair representation in energy system processes (Sovacool & Dworkin, 2014). The clean energy justice agenda comprises initiatives and polices spanning from the national level (e.g., the U.S. government's Justice40 initiative) to local grassroots efforts to promote or oppose project development. Understanding how project siting interacts with these clean energy justice efforts requires answering several open questions. In addition to the broad policy and market factors that drive solar and wind project siting at a macro scale, what are the techno- and socioeconomic factors that drive siting at a micro (e.g., sub-state) scale? What are the negative and positive impacts of project development, and are those impacts well understood? What are the equity implications of the distribution of those impacts vis-à-vis solar and wind project siting patterns?

In this article, we aim to inform this discourse by analyzing the technoeconomic drivers of solar and wind siting patterns to date. We explore how those technoeconomic factors channel projects into areas with particular demographic characteristics. We accept the ambiguous and contextual impacts of project development on host communities and avoid making simplifying assumptions about the broad equity implications of these siting patterns. Instead, we explore the equity implications of solar and wind siting patterns through multiple energy justice perspectives.

Literature Review

The literature has identified many drivers of solar and wind project siting. First and foremost, developers prioritize sites with strong solar and wind resources (IFC, 2015; Kahn, 2000; Zichella & Hladik, 2013). This reliance on spatially-heterogeneous resources distinguishes solar and wind project siting from fossil fuel project siting (Kahn, 2000). Fossil fuel project siting is generally more flexible, though proximity to fuel can influence siting and thermal plants require access to adequate water sources for cooling. In areas with suitable solar and wind resources, a host of secondary technoeconomic factors determine precisely where projects are sited. Key secondary technoeconomic considerations include policy (e.g., state renewable portfolio standards), electricity market structure, access to grid infrastructure, road access, regulatory constraints, environmental constraints, site topology, climate (Brewer et al., 2015; IFC, 2015; Outka, 2010; Sward et al., 2021), and local acceptance or opposition

(Bessette & Mills, 2021; Brewer et al., 2015; Huber et al., 2017; Rand & Hoen, 2017; Sward et al., 2021).

Local opposition to solar and wind projects stands in stark contrast to the broad societal acceptance of renewable energy. This paradox has driven research to understand local opposition to project development. Local opposition generally stems from perceived aesthetic, economic, and environmental impacts (Crawford et al., 2022), especially when these impacts occur close to populated areas, cultural areas, recreational areas, and natural ecosystems (Bessette & Mills, 2021; Carlisle et al., 2016; Huber et al., 2017). In a review of this literature, Rand and Hoen (2017) arrive at two conclusions that are particularly germane to our study. First, perceived socioeconomic benefits enhance public acceptance, such as perceptions that project development will drive economic development, create temporary construction jobs, and increase tax revenues. As a result, projects developed or owned by local companies or community organizations may garner more local support (Schelly et al., 2020; Sovacool & Ratan, 2012). Second, perceptions of fairness, justice, and transparency also determine public acceptance. Transparent processes that engage local stakeholders in siting decisions can increase public acceptance. Opaque processes can create a sense of injustice that drives local opposition (Elmallah & Rand, 2022). Feelings of injustice may be especially acute in under-resourced communities that have been excluded from such processes in the past.

A growing literature explores solar and wind project siting in the context of energy justice. Energy justice is a broad, complex, and growing field that lacks a single accepted definition (E. Baker et al., 2021). However, the field is coalescing around a framework comprising at least three tenets (Carley & Konisky, 2020; Sovacool & Dworkin, 2014). First, a just energy system fairly distributes the benefits and burdens of energy generation and consumption. Second, justice requires equitable and inclusive procedures that ensure that all relevant stakeholders can fairly participate in energy system decision-making. Third, justice requires a recognition of and remedies for historical energy system injustices. Our analysis and discussion will concentrate primarily on the first tenet of distributional justice.

The growing literature on the energy justice implications of project siting has established several recurring themes:

- Justice is rarely explicitly considered in public proceedings around project siting (Bailey & Darkal, 2018), and conflicts may emerge due to the lack of representation of under-resourced communities in project planning (Levenda et al., 2021; Yenneti & Day, 2015).
- A community's social capital correlates with ability to resist undesirable project development, such that well-resourced opponents may more successfully prevent local project development (Crawford et al., 2022) while under-resourced communities may disproportionately host projects (Anderson, 2013; Fraser, 2021; Fraser & Chapman, 2018; Roddis et al., 2018).
- Solar and wind project siting could perpetuate historical energy injustices by burdening under-resourced communities with the costs of project development, such as loss of agricultural land, local environmental impacts, aesthetic impacts, hazards from improper materials disposal, reduced access to local water resources, land dispossession, and human rights violations (Levenda et al., 2021; Robinson & Shine, 2018; Sovacool et al., 2019; Yenneti et al., 2016). Numerous

cases have been documented of injustices related to solar and wind project development, mostly in developing countries and often related to conflicts with indigenous communities (Avila, 2018; Business, 2021; Huesca-Pérez et al., 2016; Mejía-Montero et al., 2021; Velasco-Herrejon & Bauwens, 2020).

- Different generation sources pose different types and levels of injustices (McCauley, 2018; Roddis et al., 2018), and residents that live near existing wind energy projects strongly prefer them to nuclear, gas, or coal plants (Firestone & Kirk, 2019).
- Alternatively, solar and wind project siting could be a tool for energy justice (Banerjee et al., 2017; Heffron et al., 2021). The ability to flexibly site projects in or near under-resourced communities could channel the economic benefits of project development and low-cost electricity into those communities. Solar and wind projects can add value to otherwise under-utilized land (e.g., lease revenue), be compatible with other land uses (e.g., livestock grazing, some forms of farming), support local jobs, increase local tax revenue, help preserve community values, and support generational succession of farmland (Brummer, 2018; DOE, 2021; Mills, 2015; Pascaris et al., 2021).

These key themes illustrate tensions and ambiguities in the energy justice literature. All projects yield both negative and positive impacts for host communities. Whether project development is a net burden or boon to host communities is thus largely contextual. Further, there is no definitive criterion for evaluating the equity of project siting patterns. Drechsler et al. (2017), for instance, define "equitable" siting patterns as those that yield an even distribution of project capacity relative to the spatial distribution of the population. However, in a survey, the study finds that about half of respondents disagreed with this definition, instead defining equitable siting patterns as those that maximize deployment and minimize social costs, regardless of the distribution of those costs. A third potential definition could be that equitable siting patterns are those that channel project development benefits into under-resourced communities. We return to these multiple perspectives on equity in project siting in the Discussion.

Mueller and Brooks (2020) provide the study most closely resembling our own. Framing wind as an inherently unwanted land use, the authors analyze distributional injustices in wind project siting in the United States. The study finds evidence of distributional injustices related to age, education, and rurality, and mixed evidence of distributional injustices related to income and race. Our study differs from Mueller and Brooks and adds to the energy justice literature in three ways. First, we do not frame project development as an inherently unwanted land use and therefore do not assume that project siting patterns provide direct evidence of distributional injustices. Instead, we analyze the technoeconomic factors that explain project siting patterns then explore the justice implications from multiple perspectives. Second, we use a larger set of independent variables to explain project siting, as we shall discuss in the following section. Third, we build on Mueller and Brooks by studying siting patterns for both wind and solar, as well as by comparing solar and wind siting with fossil fuel siting patterns.

Materials and Methods

Our primary quantitative objective is to identify the technoeconomic factors that have driven solar and wind project siting patterns to date and how those factors may or may not create correlations between project siting and local demographics. To that end we construct three sets of variables: variables on project siting; variables for the technoeconomic drivers of historical project siting patterns; and demographic variables. The demographic variables rely largely on data from the U.S. Census collected at the tract level. For this reason, we collapse the first two sets of variables similarly to a tract level. Tracts are small enough—most tracts have 3,000-6,000 inhabitants—to capture meaningful local trends, but also large enough to contain all or substantial portions of utility-scale projects. The median Census tract size is about 450 hectares, large enough to host roughly 180 MW of solar or 25 MW of wind capacity. Our final data set comprises 60,119 tracts with complete data for all three sets of variables.

Utility-scale solar project locations come from data maintained by the U.S. Lawrence Berkeley National Laboratory. Note that these data represent large-scale, ground-mounted solar projects and exclude small-scale rooftop solar projects. Wind project locations come from the U.S. Wind Turbine Database maintained by the Lawrence Berkeley National Laboratory and the U.S. Geological Survey (Hoen et al., 2021). In both cases, we use project coordinates to assign projects to tracts using the MazamaLocationUtils package in R (Callahan, 2022). We include data for all projects installed and operational by the end of 2020. We then collapse the data to the tract level by calculating total capacity installed in each tract for each technology. The final data set covers about 36 GW of utility-scale solar and 113 GW of wind capacity. For comparison, certain analyses also include data on fossil fuel plants (coal and natural gas) compiled by the U.S. Energy Information Administration.

We quantitatively analyze the drivers of solar and wind project siting through five proxy variables defined in Table 1. These five variables are proxies in the sense that they represent underlying values for project siting drivers identified in the literature. The tract-level averages proxy for the general value of each variable within a tract but do not provide information about variation within the tract. For instance, a tract with a high average land value may have swathes of low-value land. Further, the accuracy of the distance proxies (distance to transmission, distance to protected areas) varies based on the size of a tract. Because we rely on tract centroid coordinates, these distance proxies will be more accurate in smaller than in larger tracts, all else equal. In the case of the transmission distance proxy, we also note that wind power may interconnect into distribution networks, and that these interconnection points are not reflected in our transmission data set. Further, for some projects, the closest transmission point in our data may represent a network expansion constructed on behalf of those projects, though data from Brewer et al. (2015) suggest that most projects site close to a preexisting network point. Finally, we note that all variables are meant to proxy for drivers of local (i.e., sub-state) siting decisions. Excluded from this list are state renewable energy policies that drive siting decisions across states but not between tracts.

The energy justice discourse examines social disparities exacerbated by inequitable distributions of the benefits and costs of energy systems. The discourse mostly focuses on disparities across income levels, races, and negotiating power (e.g., social capital, political power). We analyze solar and wind siting patterns as related to disparities in income and race across geographic areas and population density. For income, we use tract-level median incomes collected by the U.S. Census. For race, we use percentiles for minority populations provided by the U.S. Environmental Protection

Agency's Environmental Justice Screening and Mapping Tool. We use U.S. Census estimates for population density. For narrative simplicity, we refer to these variables as demographic factors to distinguish them from the technoeconomic siting drivers. As we discuss further, this distinction does not imply that demographic characteristics do not similarly drive project siting decisions, though the theoretical basis for a causal impact of demographic factors is weaker than the case of the technoeconomic factors. See Supplementary Materials for summary statistics of all variables.

We analyze project siting drivers through a multivariate model. The dependent variables are tract-level, cumulative installed solar and wind capacities. We focus on capacity because this metric directly describes the amount of solar or wind in a tract. In contrast, the number of projects may mask substantively distinct impacts from a relatively small (e.g., 1 MW) project versus a relatively large (e.g., 200 MW) project. We provide results of a project-level model in Supplementary Materials.

Project siting can be quantified at two levels. The first level is the binary value for whether a tract hosts a project or not. The second level is the continuous value of how much capacity is hosted by a given tract. Cragg (1971) develops a model for evaluating two-part decisions by jointly evaluating impacts on the decisions at both levels. The first part of the two-part model is a probit model to evaluate decisions at the first level, in this case the impacts of siting drivers and demographic factors on the probability that a tract hosts a project. The probit model takes the following form:

$$\Pr(h) = \alpha_0 + D\alpha_1 + X\alpha_2 + \varepsilon \quad (1)$$

Where $\Pr(h)$ is the modeled probability that a tract hosts at least one project, α_0 is an intercept, D is a vector of the potential drivers (resource quality, land value, transmission distance, protected area distance, land use), X is a vector of the demographic variables (tract median income, minority percentile, population density), α_1 and α_2 are coefficients measuring the impacts of the drivers and demographic variables on the probability of hosting projects, respectively, and ε is an error term.

The second part of the two-part model is an ordinary-least squares regression to evaluate decisions at the second level, in this case the impacts of siting drivers and demographic factors on the cumulative installed capacity within host tracts:

$$\log(mw) = \beta_0 + D\beta_1 + X\beta_2 + \epsilon \quad (2)$$

Where $\log(mw)$ is logged tract-level cumulative installed capacity, β_0 is an intercept, β_1 and β_2 are coefficients measuring the impacts of the siting drivers and demographic variables on MW installed, respectively, and ϵ is the second-step model's error term. We log the dependent variable to mitigate the impacts of the skewed distribution of cumulative installed capacity. We implement the two-part model using the twopm package in Stata (Belotti et al., 2015). We use state-clustered standard errors to control for the possibility of regulatory and other sources of variation across states.

See the Supplementary Materials for the results of several alternative specifications provided as sensitivity checks to the results.

Results

We first present descriptive results of bivariate correlations between project siting and the explanatory variables to establish intuition for the results of the multivariate models.

Descriptive results

Solar and wind project siting patterns exhibit the expected correlations with three of the four siting drivers (Figure 1). First, projects are primarily located in areas with strong resources. Tracts with above-average solar or wind resources are about 3 times (t=11.5) or 20 times (t=28.0) more likely to host solar or wind projects, respectively, than tracts with below-average resources. Second, project siting skews toward tracts with lower average land values. Tracts with below-average land values are about 6 times more likely (t=25.4) to host a project than tracts with above-average land values. Third, a disproportionate amount of capacity is sited in tracts that are relatively far from protected areas, though this relationship is driven almost entirely by wind siting. The correlation with distance from protected areas is partly explained by the fact that protected areas are less prevalent in wind-heavy states such as Texas, Iowa, and Kansas. However, even within Texas, about 85% of installed wind capacity is in the 25% of tracts furthest from protected areas.

The unexpected result is that project capacity is roughly evenly distributed with respect to transmission distance. The weak correlation could be partly explained by data limitations, given that the transmission distance data may not include distribution network points for potential project interconnection. Still, the weak correlation between transmission distance and project siting has a straightforward explanation. In our data, 99% of projects are less than 16 km from a transmission point, in line with findings fom

Brewer et al. (2015) that 85% of solar projects in the southwest U.S. are within 33 km of a transmission line. Together, these results suggest that project developers avoid extreme distances from transmission access but, as long as transmission is cost-effectively accessible, other factors determine project siting more directly than marginal differences in transmission distance.

Solar and wind project siting exhibit largely expected patterns vis-à-vis existing land uses (Figure 2). Projects skew heavily toward tracts with more undeveloped open space. Tracts where more than half of land area is classified as undeveloped are about 27 times more likely (t=36.6) to host projects than other tracts. Further, tracts where more than 10% of land area is classified as open space are about 3.5 times more likely (t=17.4) to host projects than other tracts. As a result, solar and wind projects are disproportionately sited in agricultural tracts. The propensity of projects to site in agricultural areas could have mixed implications. On the one hand, where solar and wind projects are compatible with agriculture, project development could provide additional revenue in agricultural areas. Preliminary studies have shown solar projects may improve output for certain types of agriculture (Barron-Gafford et al., 2019), and wind project development can improve farm economics (Bessette & Mills, 2021). On the other hand, project development may be viewed as incompatible with agricultural aesthetics and lifestyles, fueling public opposition (Rosen, 2021).

Solar and wind project siting correlates with local demographic characteristics in similar patterns as fossil fuel project siting (Figure 3). All three project types are under-represented in tracts with higher median incomes and, in the case of solar and fossil fuels, disproportionately installed in tracts with lower median incomes. Tracts with below-average median incomes are about 1.9 times more likely (t=11.7) to host solar or wind projects than other tracts, compared to about 1.4 times more likely (t=6.4) in the case of fossil fuel plants. This general pattern is similar when measured at smaller geographic levels: solar capacity is under-represented in high-income tracts in 26 of the 39 states with solar projects, and wind capacity is under-represented in high-income tracts in 32 of the 38 states with wind projects. Second, tracts with below-average minority shares of the population are about 3.8 times more likely (t=17.9) to host wind projects. Finally, all project types—but especially solar and wind—skew heavily toward tracts with low population densities. Tracts with below-average population densities are about 75 times more likely (t=37.9) to host solar or wind projects, compared to about 5 times more likely (t=23.7) to host fossil fuel plants.

As solar and wind deployment expands, one would expect project siting to evolve as ideal sites are exploited by earlier projects. The data provide little evidence of such a shift in project siting to date. All the correlations discussed above have been relatively stable to date, though it is worth noting that at this early stage of technology diffusion solar and wind projects have only been sited in 3% of all tracts in the dataset.

Multivariate model results

Table 2 provides the results of the two-part regression model. Models (1) and (3) provide the results of the first part (Equation 1) for solar and wind, respectively, while models (2) and (4) provide the results of the second part (Equation 2). All independent variables are standardized in all models, such that each coefficient represents the effect of a standard deviation change in the independent variables. The coefficients in models (1) and (3) are interpreted as the change in the odds of a tract hosting a solar or wind project given a standard deviation change in the associated variable. Although probit coefficients lack a straightforward interpretation because the variables are standardized these coefficients can be roughly interpreted as the change in the z-score from a standard deviation change in each variable from its mean. Positive coefficients in models (1) and (3) imply that the variable is associated with an increased likelihood that a tract hosts at least one solar or wind facility. The coefficients in models (2) and (4) are interpreted as the percentage change in installed solar or wind capacity in a tract given a standard deviation change in the associated variable. Again, positive coefficients in models (2) and (4) imply that the variable is associated with more installed capacity in tracts that host at least one solar or wind project.

Focusing first on the siting drivers, the models show that resource quality and access to undeveloped land have the strongest effects on project siting. Converting the z-score coefficients to probabilities, the first-part models suggest that a standard deviation increase in resource quality from the mean increases the probability that a tract hosts a solar or wind project by about 12% or 50%, respectively. The stronger relationship between wind siting and wind speeds likely reflects the fact that the wind resource is much more spatially variable than the solar resource; tract-level wind speeds span about a factor of six in the data, compared to about factor of two in the case of solar insolation. Further, wind output is roughly proportional to the cube of wind speeds, meaning that levelized costs of wind electricity exhibit increasing returns to the wind resource. Similarly, a standard deviation reduction in the share of developed land from the mean increases the probability of hosting a solar or wind project by about 17%

or 27%, respectively. In the case of wind, a standard deviation increase in the share of undeveloped open space increases the probability of hosting by about 17%, compared to a 3% increase for solar. Again, the stronger relationship in the case of wind likely reflects the larger land requirements of wind projects; a typical utility-scale wind project requires about 18 hectares per MW of capacity, compared to about 2.5 hectares for solar (NREL, n.d.). Finally, the models provide mixed evidence on whether land values and distances from protected areas drive project siting when controlling for other factors. Unlike the descriptive statistics, the land value coefficients are insignificant in every model. It is worth noting that land values correlate with land uses, such that collinearity may mitigate the estimated effects of land value on project siting. In the case of protected areas, whereas we use a single variable to proxy for all protected areas in our models, future research could explore whether specific types of protected areas (e.g., biological, cultural, recreational) are more likely to affect project siting than others.

Moving onto the demographic factors, the models show that population density has the strongest association with project siting patterns. A standard deviation reduction in population density increases the probability of a tract hosting a solar or wind project by about 99% and 95%, respectively, though the result is statistically insignificant for wind. Siting patterns exhibit weaker associations with income and race. A standard deviation reduction in median income increases the probability of a tract hosting wind project by about 13%. Solar projects are more likely to be sited in tracts with larger minority shares of the population. The correlation between solar siting and minority populations is likely due, in part, to the large number of solar projects in the relatively racially diverse U.S. southwest. Still, the coefficient on minority share generally remains positive when limiting the data to regional sub-samples (see Supplementary Material).

The results of the second-step model generally agree with the results of the first-step model. That is, factors that increase the probability of project hosting are generally also associated with larger project sizes in tracts that host projects. One notable exception is that tracts with more undeveloped open space are not associated with more solar capacity. This null result is driven by a set of relatively large solar projects installed in areas of Florida with more land cover classified as wetlands and open water. Because wetlands and open water are parts of the base category defining the land use variables in the model (see Table 1), the preponderance of large projects in the base category in Florida results in a negative, though insignificant, correlation between project siting and open spaces in Florida.

The relationships between the drivers and demographic factors and project siting are generally consistent across solar, wind, and fossil fuel generators (Figure 4), and across regions (see Supplementary Material). All technologies exhibit clear skews toward tracts with more undeveloped space, as well as tracts closer to transmission. Further, solar, wind, and fossil exhibit similar patterns with respect to the demographic factors: all three technologies skew toward tracts with lower median incomes and lower population densities. The one exception is the correlation between solar siting and tracts with larger minority shares of the population.

In the two-part model, the demographic characteristics do not necessarily have a causal impact on project siting. Developers and regulators could actively consider demographic characteristics during project planning and siting decisions. However, at least some of the demographic relationships reflect spurious correlations with other factors that determine project siting, namely the need for undeveloped open spaces. To further analyze how technoeconomic factors can drive projects into areas with particular demographic characteristics, we predicted the demographics of project-hosting tracts based only on the siting drivers. That is, we use the first-part Probit model to predict the probability that every tract will host a project based only on tract resource quality, land value, transmission distance, protected area distance, and land use. We then weighted the mean demographic characteristics of project-hosting sites based on the predicted hosting probabilities. This exercise shows that technoeconomic constraints channel solar and wind projects into sparsely populated areas and, to a lesser extent, areas with relatively low incomes and relatively small minority populations (Figure 5). These predicted patterns are like those of fossil fuels, except that fossil fuel plants tend to site in relatively more densely populated areas.

The two-part models explain 23-41% of the variation in project siting patterns, as indicated by the model R^2 values. While the R^2 values do not affect the interpretation of coefficients, the R^2 values indicate that myriad other factors drive project siting patterns. Much of the unexplained variation could reflect the uncertainties of human behavior and its influence on project siting decisions. Future research could explore an expanded set of potential siting drivers.

Discussion

Our results confirm that solar and wind siting patterns are driven primarily by technoeconomic factors, especially access to strong resources and open undeveloped spaces. Wind siting is particularly constrained, given the greater variation in the wind resource across space and the need for larger open areas for wind project development. Future solar and wind project siting patterns will be similarly constrained. Solar and wind siting patterns have limited flexibility to meet other societal objectives such as equity while maintaining a pace and scale of deployment consistent with climate change objectives. Technoeconomic siting constraints will channel solar and wind projects into areas with low population densities and, to a lesser extent, areas with lower income levels and relatively smaller minority populations. What, then, are the implications of these siting patterns from an energy justice perspective?

Given that the local impacts of project development are largely ambiguous and contextual (see Literature Review), both in terms of project location and technology (i.e., solar or wind), we avoid making broad generalizations about the implications of our results. Instead, we explore our results along a continuum of perspectives from the literature framing project hosting as mostly negative to hosting as mostly positive:

- **Project hosting is mostly negative:** Project development can compromise local land uses, restrict access to local resources, and otherwise burden host communities with the external costs of the clean energy transition (Levenda et al., 2021; Mueller & Brooks, 2020; Sovacool et al., 2019; Yenneti & Day, 2015). From this perspective, our results suggest that solar and wind project siting could impose these burdens on rural communities, and to a lesser extent on low-income communities. These potential injustices reinforce the need for transparent processes that fairly engage local stakeholders in host communities.
- **Hosting is neutral:** Most survey respondents in Drechsler (2017) viewed the pace and scale of project development as the primary factor in the equity of

project siting decisions rather than the locations of specific projects. This result suggests that project hosting could be considered neutral from an equity perspective. Viewed this way, our results indicate that solar and wind project siting is driven primarily by technoeconomic factors, as would be expected. By exploiting the strongest resources in areas that can support large-scale projects, existing siting patterns may drive grid decarbonization more rapidly and cost-effectively than any other siting patterns. From this perspective, one could argue that these siting patterns are just insofar as they maximize the global benefits of solar and wind deployment over a given timeframe or for a given investment, including benefits from mitigated climate change damages in vulnerable communities.

- **Hosting is mostly positive:** Project development can be a boon for host communities, providing numerous local economic and community benefits (Brummer, 2018; DOE, 2021; Pascaris et al., 2021). From this perspective, existing solar and wind siting patterns present an opportunity to enhance energy justice in rural, low-income communities. Our results show that likely hundreds of gigawatts of solar and wind projects will be developed in rural and often relatively low-income communities in the coming decades. In the case of solar, the results also suggest a slight skew toward communities with larger shares of minorities. Project development could provide a boon to these economies in the form of lease revenues, tax revenues, and temporary construction jobs. Communities could maximize local benefits through active engagement in project planning and development (Banerjee et al., 2017; Brummer, 2018; Heffron et al., 2021). One potential model is the community energy approach, where community groups proactively plan and implement local renewable energy development. Community energy hosting has been associated with numerous benefits (Brummer, 2018), including achieving energy justice objectives such as reducing energy poverty (Hanke et al., 2021). Conversely, insofar as project development is a boon to host communities, our results suggest that the benefits of wind development are bypassing communities with relatively large minority populations.

Finally, it is worth noting that we find both similarities and differences between siting patterns for solar, wind, and fossil fuel plants. All projects are similar in their skew toward more sparsely populated areas with more undeveloped space and access to transmission. However, solar and wind projects differ substantially in their reliance on spatially heterogeneous resource flows and the need for much larger open spaces. As a result, fossil fuel plant siting occurs largely in an urban fringe and suburban context, whereas solar and wind project siting occurs largely in a rural context, with some clear exceptions such as rural coal plants and solar installed in urban spaces.

We conclude by suggesting areas for future research based on the three research questions posed in the introduction. Future research could explore whether project siting drivers vary across different regions, a possibility suggested by sensitivity analyses presented in Supplementary Materials. Future research could implement similar analyses with more technologies such as offshore wind, whose siting is likely driven by distinct factors and may have unique impacts on host communities. Future research could seek to resolve existing tensions and ambiguities around the impacts of solar and wind project development on host communities. If these impacts are indeed contextual, what determines when projects pose more burden than benefit, or vice-versa? How can projects be structured to maximize the benefits of hosting over the burdens, such that solar and wind project siting patterns represent an opportunity to improve rather than impede energy justice? Future researchers could analyze disparities between existing siting patterns and equity-optimal patterns. If that disparity is very large, researchers could explore interventions to nudge siting patterns in a different direction, though future siting patterns will continue to be constrained by technoeconomic factors.

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Declaration of interests

The authors declare no competing interests.

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Tables

Table 1. Variable Definitions for Project Siting Drivers

Variable	Definition	Source
Resource quality	Tract-level averages for solar insolation (kWh/m^2/day) and wind speed at 100 meters	U.S. National Renewable Energy Laboratory technical potential data
Land value	Tract-level average assessed land value ($/hectare)	CoreLogic
Distance from transmission	Distance from every tract (using centroid coordinates) to the nearest point on a transmission network	Hitachi Velocity
Distance from protected areas	Distance from every tract to the closest area protected for natural, recreational, or cultural uses. This variable provides a proxy for strategies to avoid public opposition due to proximity to protected areas.	U.S. Geological Survey's Protected Areas Database

Land use	The percentage of surface area dedicated to developed land (developed open space, developed low intensity, developed medium intensity, developed high intensity), agriculture (pasture, cultivated crops), and undeveloped open space (barren land, grasslands, scrublands, and perennial ice/snow). Note that some undeveloped open spaces may serve as livestock rangeland. The base (i.e., omitted) variable for the purposes of the regression includes forests, wetlands, and open water. We used these categories as the base variable given that these are the land uses least likely to provide viable sites, though it is worth noting that some wind projects have been sited in forests (Bunzel et al., 2019).	U.S. Geological Survey National Land Cover Database

Table 2. Two-Part Model Results

	(1) Part 1 Y=solar host	(2) Part 2 Y=log(solar MW)	(3) Part 1 Y=wind host	(4) Part 2 Y=log(wind MW)
Resource quality	0.15*	0.44*	0.68*	0.56*
	(0.03)	(0.07)	(0.04)	(0.09)
Land value	0	0.03	0.08	-0.48
	(0.07)	(0.09)	(0.06)	(0.34)
Transmission dist.	-0.02	-0.03	-0.01	0.02
	(0.01)	(0.02)	(0.01)	(0.04)
Protected area dist.	-0.02	0.04	0.05*	0.07*
	(0.01)	(0.04)	(0.01)	(0.02)
Land use: developed	-0.21*	-0.28*	-0.34*	-1.32*
	(0.08)	(0.13)	(0.12)	(0.22)
Land use: agriculture	0.03	-0.05	0.29*	0.27*
	(0.02)	(0.05)	(0.02)	(0.04)
Land use: open space	0.04*	-0.07	0.21*	0.26*
	(0.02)	(0.04)	(0.02)	(0.04)
Income	0.02	-0.09	-0.16*	-0.26*
	(0.03)	(0.06)	(0.04)	(0.12)
% minority	0.25*	0.1	-0.04	0
	(0.03)	(0.07)	(0.04)	(0.08)
Population density	-3.55*	-2.96*	-1.97	-0.68
	(0.66)	(0.85)	(1.11)	(1.64)
Pseudo R^2	0.23		0.41	
R^2		0.24		0.33

* p<0.05

Figures

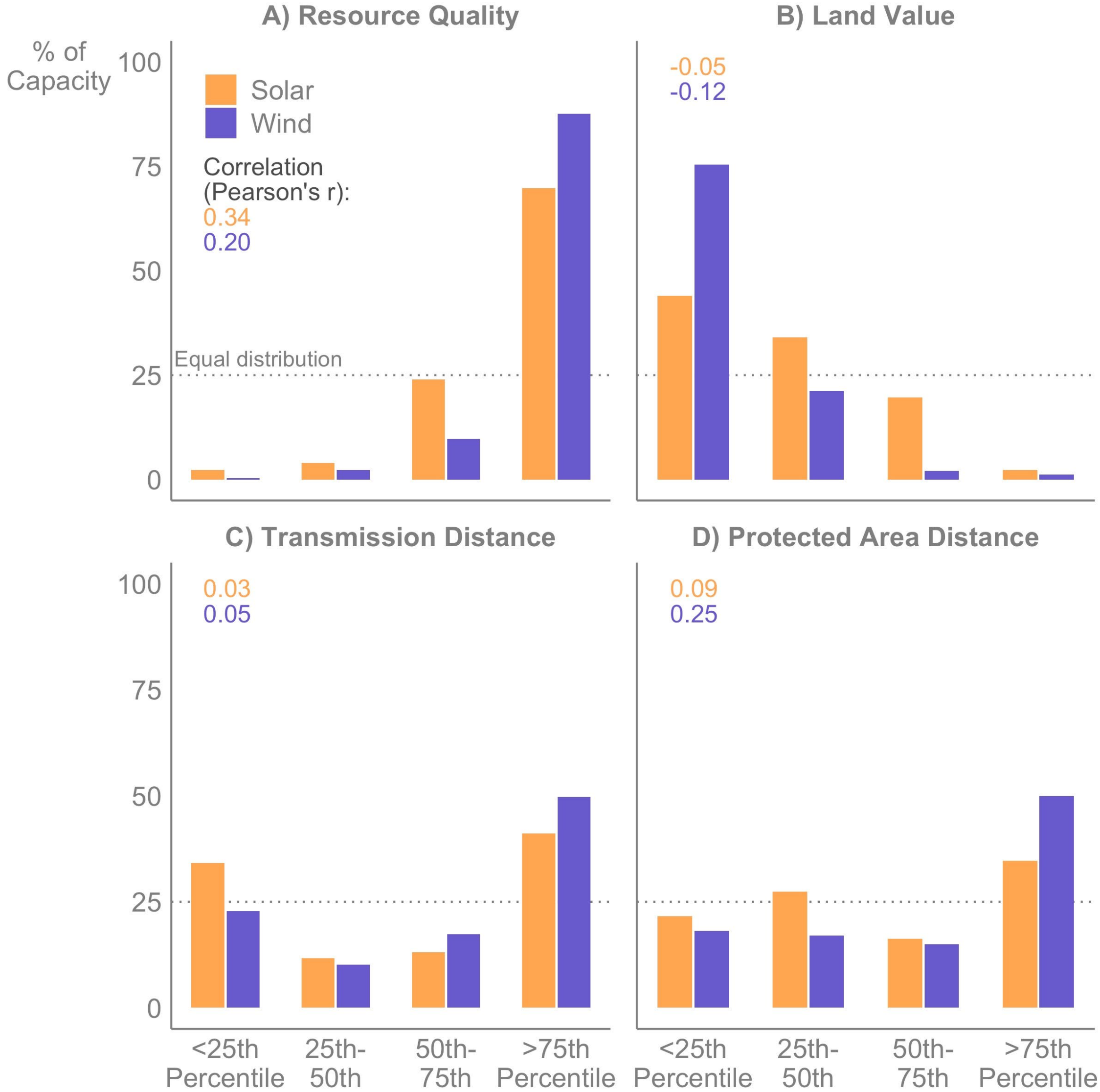

Figure 1. Distributions of wind and solar capacity by potential drivers. This figure distributes combined solar and wind capacity (MW) across the quartiles for each of the four potential drivers of solar and wind project siting. The bars to the far left of each figure represent capacity in the 25% of tracts with the lowest values of each driver, while the bars in the far right represent capacity in the 25% of tracts with the highest values of each driver. The horizontal line of "Equal distribution" represents the point at which all bars would align if capacity were equally distributed with respect to each factor.

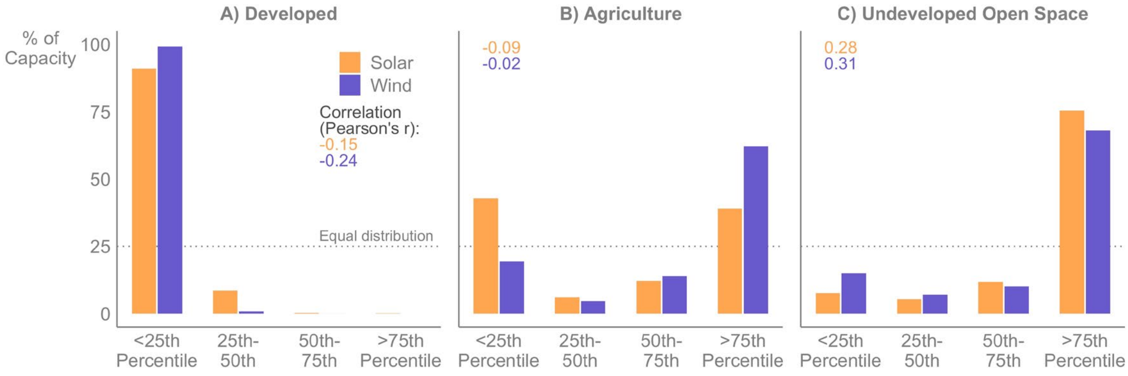

Figure 2. Distributions of wind and solar capacity by existing land uses. This figure distributes combined solar and wind capacity (MW) across the quartiles for each of the three land-use categories. Quartiles based on percentages of tracts dedicated to each land use. For instance, the <25th percentile in pane A refers to the 25% of tracts with the least are dedicated to developed spaces.

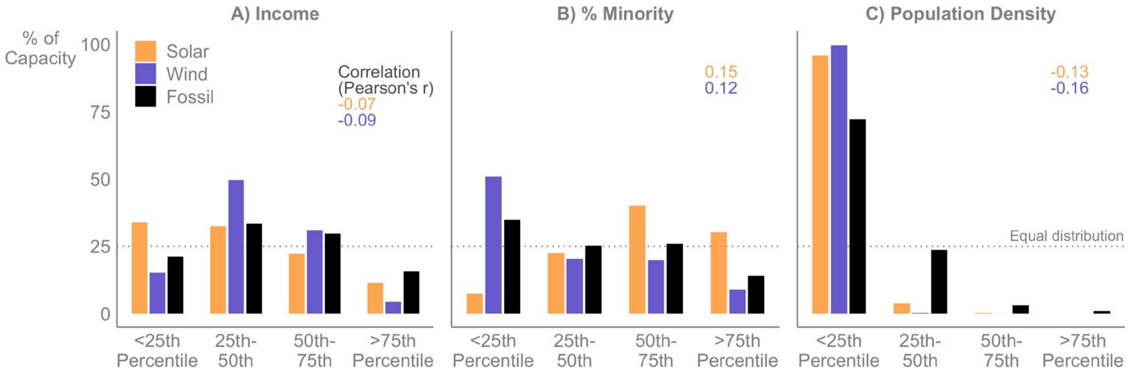

Figure 3. Distributions of renewable and fossil fuel capacity by demographic metrics. The bars in this figure depict combined solar and wind capacity (MW) across the quartiles for each of the three demographic variables. The black diamonds depict combined coal and natural gas capacity.

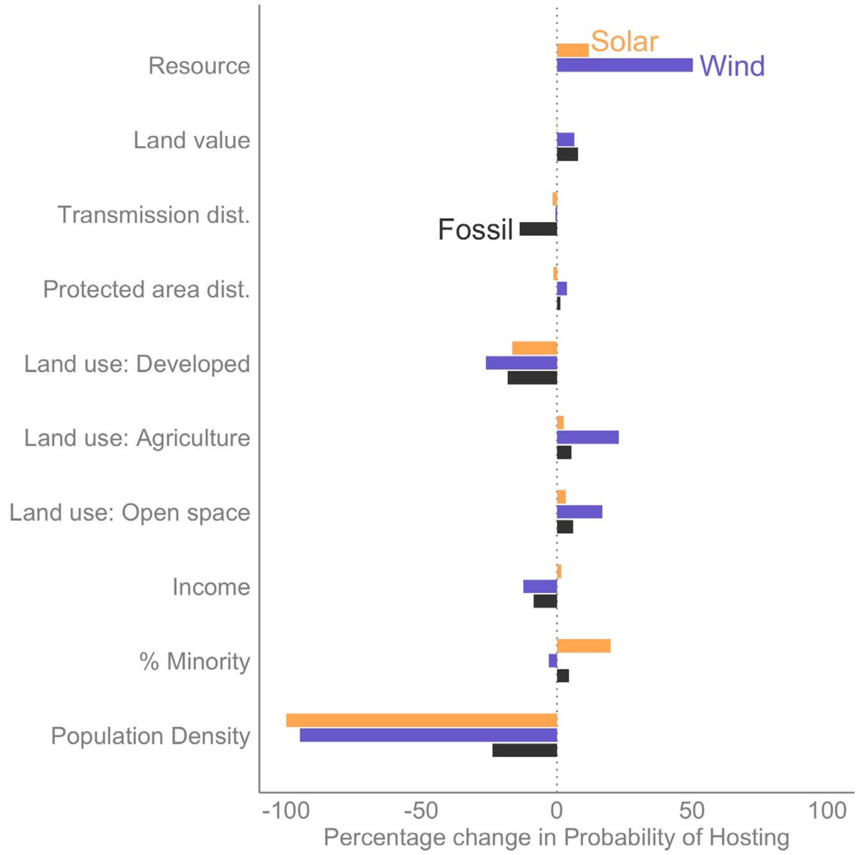

Figure 4. Visual representation of probit model results. For simplicity, the coefficients are converted into percentage changes in probabilities of hosting based on standard deviations from mean values.

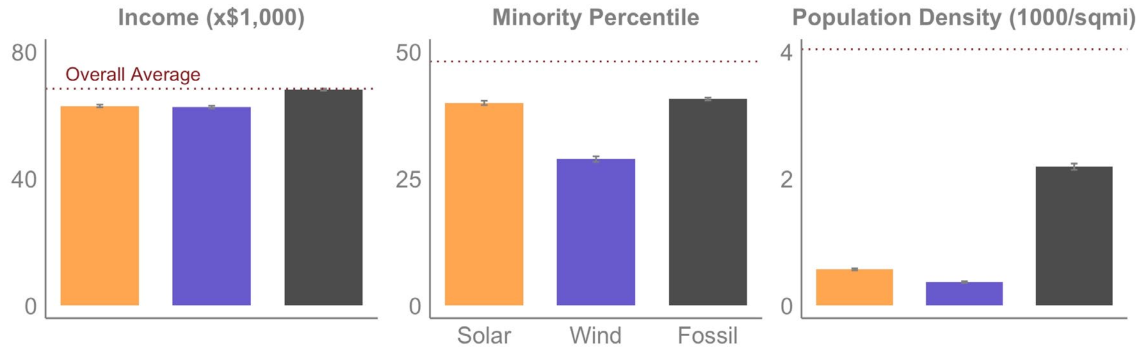

Figure 5. Predicted demographic characteristics of project-hosting tracts. Bars represent predicted means weighted by prediction scores from the first-part of the two-part model. Error bars represent 95% confidence intervals based on weighted standard errors.