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The Energy Transition for Oil- and Gas-Producing Tribal Nations: Assessing Options for Energy Development with the Southern Ute Indian Tribe

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Working Paper 25-18
June 2025

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Acknowledgements

We would first like to thank the Southern Ute Indian Tribe for their collaboration and partnership. We would particularly like to thank Kourtney Hadrick and Graham Stahnke from the Southern Ute Growth Fund for sharing their time, expertise, and data to make this collaboration possible. We are grateful to the Alfred P. Sloan Foundation for funding this work under Grant No. G-2023-22367, and we appreciate our collaborators, led by Monika Ehrman (SMU) and Andrew Curley (Diné, University of Arizona), as well as team members Alana Davicino (Indiana University), Catherine Hausman (University of Michigan), Monte Mills (University of Washington), Angela Parker (Mandan/Hidatsa/Cree, University of Denver), Pilar Thomas (Pasqua Yaqui, Quarles & Brady), and Margaret Walls (RFF). In addition, RFF's Nicholas Roy provided valuable assistance with renewable energy subsidy analysis.

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Abstract

This paper presents the results of a multi-year collaborative research project between the authors, several other researchers, and the Southern Ute Indian Tribe, a natural gas-producing Tribe whose Reservation sits near the "Four Corners" region of southwestern Colorado. In this collaboration, we worked with the Tribe to inform their decision-making about future energy development by producing multiple scenarios depicting the potential for natural gas, wind, and solar development on their Reservation. We find that natural gas production on the Reservation—absent the development of new shale formations—declines under all scenarios through 2050, as do associated Tribal revenues. We also find that solar—but not wind—development may be economically viable on parts of the Reservation. Along with these quantitative results, we believe that our collaborative research approach may serve as a model for other scholars who wish to work with Tribal nations within the United States as they seek to ensure their sovereignty in a changing energy landscape.

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1. Introduction

There are over 500 federally recognized Tribal Nations and Alaskan Native entities within the borders of the United States, all with distinct histories, cultures, and priorities. These nations also face distinct opportunities and challenges in a changing energy landscape. Opportunities include the potential to improve access to affordable and reliable energy (Aklin et al. 2021), to address a legacy of environmental damage associated with energy development (e.g., Hoover et al. 2017; Roscoe et al. 1995), and to benefit from increased deployment of transitional energy technologies (e.g., Brookshire and Kaza 2013; Lee et al. 2023; Parker et al. 2024).

At the same time, some Tribal Nations are major producers of coal, oil, and natural gas (Raimi and Davicino 2024). Transitioning away from these energy sources, as world leaders agreed to do in 2023 (UNFCCC 2023), would create new challenges for these nations. One such nation is the Southern Ute Indian Tribe (hereafter the Tribe), which has been a large producer of natural gas for decades and whose reservation sits near the Four Corners region of the United States in southwestern Colorado. This analysis is the result of a multiyear collaboration among the authors, several additional researchers[1], and the Tribe, which is pursuing a range of innovative strategies to adapt to changing domestic and global energy markets. We produced this work in a joint effort with our partners using a range of analytical and modeling tools that we describe in Section 2.

The goals of this analysis are threefold. First, we seek to provide useful information to the Tribe as it considers its options for future energy development. Second, we hope that our analysis and the policy implications that derive from it can inform other decisionmakers in oil- and gas-producing regions, including at the local, state, Tribal, and federal levels. Third, we hope that our collaborative research approach offers a model for other scholars to engage productively with Tribal Nations as they seek to navigate a complex and rapidly changing energy landscape.

1.1. About the Southern Ute Indian Tribe

The Ute people's historic lands cover most of present-day Colorado, along with large portions of Arizona, New Mexico, and Utah. After centuries of interactions with European settlers, Ute lands were formally reduced through a series of treaties with the US government beginning in 1868. Ultimately, various Ute bands were separated and moved to three reservations: the Uintah and Ouray Ute Reservation in Utah, the Ute Mountain Ute Reservation, and the Southern Ute Indian Reservation (the "Reservation"), the last two in southwestern Colorado (Southern Ute Indian Tribe 2024). The Reservation occupies just over 1,000 square miles, with land and minerals within the reservation held in a checkerboard pattern by various owners, including the Tribe, individual Tribal members, non-Tribal individuals, and the federal government.

1 See acknowledgements for a list of our collaborators.

In 1949, mineral leasing began on the Reservation, primarily for natural gas production, with oversight from the US Department of Interior. Production continued for several decades, with the tribe receiving royalties from natural gas production (Baker 2023). In the 1970s, however, the Tribe was one of several to issue moratoriums on new leasing. From 1974 through 1984, the Tribe worked with a variety of technical experts to develop a better understanding of the quality of its natural gas resource and enhance its governance capacity. In 1984, when leasing resumed, the Tribe was better positioned to negotiate favorable terms with private operators and conduct more robust oversight of royalty compliance, a major issue for energy-producing tribes (Grogan et al. 2011). The Tribe also had instituted a severance tax in 1982 that went on to generate more than $900 million through 2023 (Baker 2023).

Thanks in part to the revenues created by these new policies and programs, the Tribe continued to enhance its internal capacity. In 1992, it established the tribally owned Red Willow Production Company, which develops, operates, and invests in over 1,800 oil and gas wells, both on and off the reservation, including in the Permian Basin and Deepwater Gulf.[2] In 1994, the Tribe invested in, and is now the majority owner of Red Cedar Gathering Company, which today operates gathering, processing, and gas treatment on the Reservation (Baker 2023). These companies allow the Tribe to exercise greater control over the development of its own resources, known as energy sovereignty, which is a critical concept for many tribes who seek to determine their own energy future (Raimi and Davicino 2024).

The revenues generated by the Tribe's leasing, royalty, and business activities provided additional opportunities. In 1999, the Tribe separated its government from its business enterprises and established the Southern Ute Growth Fund, making it easier to separate investment decisions from political considerations. By 2001, the Tribe had become the first Tribal Nation to receive an AAA credit rating (Southern Ute Indian Tribe 2024), and by 2022, the Growth Fund held more than $3.4 billion in assets (Fitch 2022).[3]

These successes allow the Tribe to provide a variety of benefits to its members, such as guaranteed employment, free college, and substantial annual per capita payments to all enrolled members. Financial resources have also enabled the Tribe to invest in on-reservation education, cultural programs, new housing, and other amenities that benefit community members.

As of late 2024, the Tribe is investing in a variety of new energy-related endeavors. For example, one project captures methane emissions from a natural seep from the Fruitland Coal Formation on the reservation, which the Tribe estimates releases nearly 6 million metric tons of carbon dioxide equivalent annually (Southern Ute Indian Tribe Air Quality Division 2024).[4] Converting captured methane to carbon dioxide generates emissions reduction credits, an additional source of income for the Tribe. The Tribe is

2 See **https://www.rwpc.us/**.

3 The Tribe's credit rating was reaffirmed as AAA in March 2025 (Fitch 2025).

4 Assuming a 100-year global warming potential of 29.8.

part of a larger Tribal consortium that was awarded $50 million in grant funding from the US Environmental Protection Agency to reduce methane and other air emissions from ongoing operations (EPA 2024).

Looking forward, the future of on-reservation natural gas production is uncertain. In recent years, production has fallen substantially, from roughly 400 billion cubic feet (bcf) annually in the early 2000s to less than 200 bcf in 2023.[5] However, the Tribe is pursuing an "all of the above" approach to energy development. This approach includes assessing and developing new natural gas resources, particularly the Mancos Shale Formation, as well as exploring the potential for enhanced geothermal energy development. Additionally, the Tribe has installed, with financial support from the US Department of Energy, one small (800 kilowatt) solar photovoltaic system on the reservation (DOE 2015) and continues to explore additional energy opportunities.

2. Data and Methods

2.1. Collaboration with the Southern Ute Indian Tribe

Since 2022, we have worked with the Tribe's Department of Energy, part of the Growth Fund, to develop modeling scenarios that inform their decisions on future energy development, specifically regarding natural gas, wind, and solar. The collaboration began with a series of meetings in which the research team sought to understand the priorities of Tribe's leadership regarding future energy development and to communicate the available modeling tools. In the following months, the research team worked with the Tribe to gather necessary data (e.g., information on land/minerals ownership, tax policies, culturally significant sites) and then develop a suite of stylized scenarios (with input from the Tribe) that we describe in the following sections.

Because some of these data include sensitive information, not all data requested by the research team (e.g., specific locations of cultural or archaeological sites, certain information on tribally owned businesses) were made available. The research team also signed a nondisclosure agreement with the Tribe to access other sensitive information that informed our analysis but that we cannot republish or share. In all cases, we respect the sovereignty of the Tribe as owners and stewards of this sensitive information.

We prepared draft results from these scenarios, which we shared with our research colleagues and the Tribe to gather additional feedback. Because of the importance of Tribal sovereignty, we have allowed the Tribe's experts to review the information included in this and other research outputs to ensure that no published information would in any way impede the ability of the Tribe to make decisions about the future

5 Statistics based on authors' analysis of data from Enverus, a proprietary source of oil and gas data and analytics.

of energy development on the Reservation. At the same time, all technical decisions regarding modeling methods, inputs, and analysis were developed independently by the research team. Therefore, all the results and conclusions included in this analysis are attributable solely to the authors and do not necessarily reflect the views of the Tribe.

2.2. Oil and Gas Production

The Reservation sits within the San Juan Basin, which includes numerous oil- and gas-bearing formations at varying depths. To model future oil and gas production on the Reservation, we rely on a version of the Dynamic Oil and Gas Market Analysis (DOGMA) model, which was developed by Prest and has been deployed in various studies (e.g., Newell et al. 2019; Prest et al. 2024; Prest 2022). For details on this modeling methodology, see Appendix A.

To summarize, the model uses historical data to estimate future production from existing wells on the Reservation based on historical decline curves from these wells. It also uses historical data to estimate drilling elasticities that determine whether, and to what extent, changes in oil and natural gas prices lead companies to drill new wells in the model. Production from new and existing wells is combined to estimate aggregate on-Reservation production into the future. DOGMA also uses geospatial data to distinguish among production occurring from minerals owned collectively by the tribe, those owned by private individuals, and those owned by the federal government.[6]

We model on-Reservation production from 2023 to 2050 under four oil and gas price scenarios based on widely used projections from the International Energy Agency (IEA 2023) and the US Energy Information Administration (EIA 2023a). These scenarios represent a broad but plausible set of future prices and reflect, to some extent, the uncertainty surrounding future demand for hydrocarbons in a world where global leaders seek to reduce greenhouse gas emissions. The IEA scenarios, in particular, reflect scenarios in which global demand for oil and gas declines to varying degrees, which in turn reduces prices for these commodities. We use the following four scenarios, ordered here from highest to lowest price:

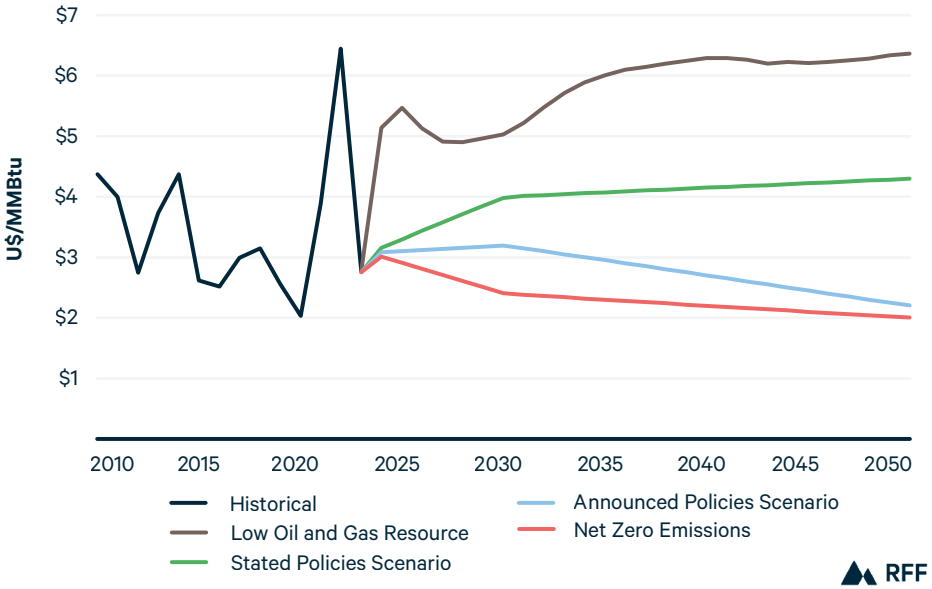
- EIA's Low Oil and Gas Resource (LOG). Assumes that ultimate recovery from US oil and gas resources is 50 percent lower than the EIA's assumptions under its reference case, resulting in higher domestic natural gas prices and, to a lesser extent, higher global oil prices.
- IEA's Stated Policies Scenario (STEPS). Incorporates international governments' existing and announced emissions mitigation policies but does not assume that they achieve more aspirational targets. Global oil and gas demand remains roughly flat by 2050.
- IEA's Announced Policies Scenario (APS). Assumes that governments will fully meet the targets and timelines for emissions reductions they have specified in their Nationally Determined Contributions under the Paris Agreement. Global oil and gas demand fall by roughly 47 and 42 percent, respectively, by 2050.

6 The development of oil and gas minerals owned by the State of Colorado on the reservation is negligible.

- IEA's Net Zero Emissions (NZE). Represents a pathway where the world's energy system changes rapidly to "limit global temperature rise to 1.5°C by 2100 (with at least 50 percent probability) with limited overshoot" (IEA 2023). Global oil and gas demand both fall by roughly 78 percent by 2050.

Because most hydrocarbon production on the Reservation is natural gas, rather than oil, drilling decisions in the model are made entirely based on the projected price of natural gas. Figure 1 illustrates natural gas prices under our four scenarios.[7]

Figure 1. Natural Gas Prices Under Four Modeled Scenarios



Sources: EIA (2023b) for Historical and EIA (2023a) for LOG; IEA (2023) for all others.

Notes: MMBtu = million British thermal units. "Historical" represents nominal Henry Hub spot prices.

2.3. Oil and Gas Revenue

Oil and gas production generates revenues for the Tribe through three main channels. First, the Tribe applies a severance tax of 6.5 percent to the value of natural gas produced on the Reservation, with three exceptions (see Appendix B for details). Those exemptions are for the value of royalties generated from minerals owned by the Tribe or Tribal members; on-lease use (e.g., for powering on-site equipment); or cross-lease beneficial use (e.g., natural gas injected to enhance production from another lease).

7 Natural gas produced on the Reservation typically receives the San Juan Basin Indian Index, a price calculated each month by the federal Office of Natural Resource Revenue, pursuant to 30 CFR 1206.172. We use Henry Hub pricing in our scenarios because Indian Gas Index prices are not available in the projections we use. Our analysis of historical data reveals that these two prices are highly correlated, suggesting that Henry Hub and the Indian Gas Index are likely to move together.

Second, the Tribe receives royalties when natural gas is produced from Tribal minerals.[8] The Tribe reports that the royalty rate it receives is governed by 30 CFR 1202.150, and we assume a royalty rate rising linearly from 12.5 percent in 2022 to 16.67 percent in 2032.

Third, the Tribe owns, in part or in full, two energy companies operating on (and off) the Reservation: Red Willow Production Company and Red Cedar Gathering Company. These companies generate revenue through their business activities, which flows to the Growth Fund. However, the Tribe treats business information for these privately owned companies as proprietary and does not wish to provide information that could reveal details of the companies' revenues, profits, or other financial information.

2.4. Wind and Solar

To assess the potential for utility-scale wind and solar development on the Reservation, we follow and adapt methodologies from prior research. Specifically, we follow methods established by the National Renewable Energy Laboratory (NREL) (Milbrandt et al. 2018) and related analysis of wind and solar development under various scenarios of land use constraint (Doris et al. 2013; Grue et al. 2021; Lopez et al. 2021).

Based on input from the Tribe and following the literature noted above, we developed three scenarios to convey the potential for deploying these resources: (1) technical, which represents the maximum build-out and is limited primarily by physical constraints; (2) reference, which incorporates some basic real-world constraints (e.g., critical wildlife habitat sites are excluded); and (3) limited, which is more restrictive and considers additional land use protections or infrastructure requirements (e.g., prime farmland sites are excluded and larger buffers are applied to water bodies). For details on our methods, see Appendix C.

As noted in Section 2.1, data limitations prevent us from accounting for the specific locations of cultural, religious, or archaeological sites on the Reservation. We respect the rights and authority of the Tribe as owners and stewards of this sensitive information but note that its omission means that our modeling results could include wind and solar development on sites that the Tribe does not wish to develop.

To assess the economic potential of wind and solar development on the Reservation, we calculate the levelized cost of energy (LCOE) for each site using data and projections from NREL (NREL 2023b,c), then compare those LCOEs with national benchmarks. Although this analysis is limited in a variety of ways (e.g., it does not account for interconnection costs or region-specific market dynamics), it was designed to inform the Tribe as to whether wind or solar development was "in the ballpark"

8 The Tribe receives royalties from Tribally owned minerals and those held in trust for the Tribe by the federal government. Other mineral rights on the reservation may be held in trust by the United States for the benefit of individual Tribal allottees or privately owned in fee; however, data limitations prevent us from estimating mineral revenues flowing to individual Tribal members from these interests.

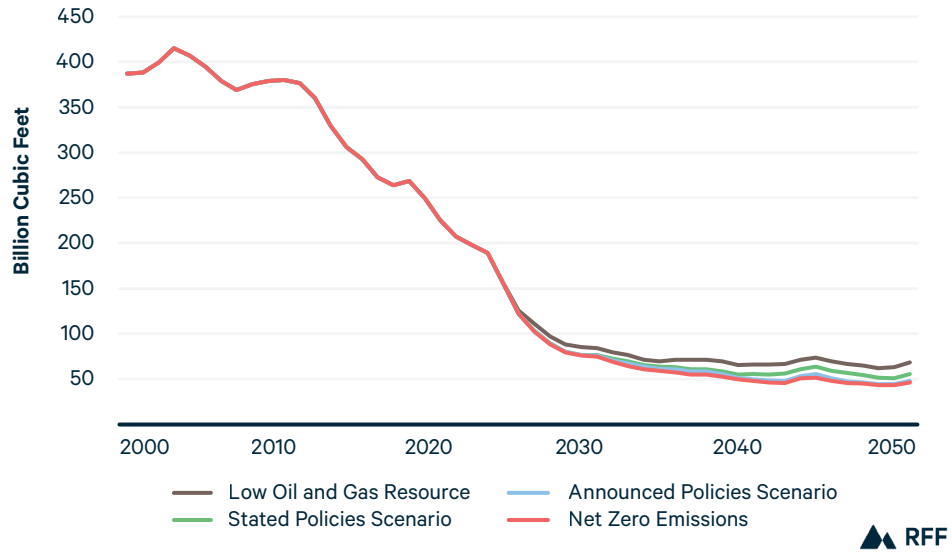
and worthy of further consideration. Additional financial analysis, legal analysis, and community engagement would be needed to determine conclusively whether development is desirable on any given site.

3. Results and Discussion

3.1. Oil and Gas Production

Our modeling results project that on-Reservation natural gas production from currently producing formations declines substantially under all four scenarios (Figure 2; oil production is de minimis under all scenarios). By 2050, natural gas production ranges from 46 to 68 bcf annually, compared with production of roughly 200 bcf in 2022. These declines reflect recent history, as on-Reservation production declined from nearly 400 bcf in 2000 to roughly half that level in recent years.

Figure 2. Modeled Natural Gas Production



Our review of historical data and conversations with the Tribe's experts indicate that these declines are mostly the result of falling productivity from the more than 2,500 coalbed methane wells that have been drilled across the Reservation. Although a modest number of new wells are drilled under each scenario, production from new wells is not sufficient to offset declines from older ones. These results are broadly consistent with the expectations of the Tribe's experts regarding production from existing formations.

However, the Tribe has indicated that it is eager to pursue new sources of natural gas production in the coming years, particularly the Mancos Shale Formation, which geologists have assessed to hold substantial oil and gas resources in the San Juan Basin and, farther north, in Colorado and Utah's Piceance and Uinta Basins (Hawkins et al. 2016; Ridgley et al. 2013). From 2015 through June 2025 (the time of this writing), operators drilled roughly 250 (mostly horizontal) wells into the formation, just two of which were drilled within the Reservation's borders (both in 2023–24 and on fee land). Our analysis of Mancos natural gas wells drilled recently (between 2022 and 2024) both on and off the reservation indicates that they can be highly productive, with production rates from a substantial proportion of wells rivaling those from prolific shale formations such as the Haynesville and Marcellus.[9] If the Tribe is able to develop the Mancos at scale, it could mitigate or even reverse the steep production declines seen in our modeled scenarios.

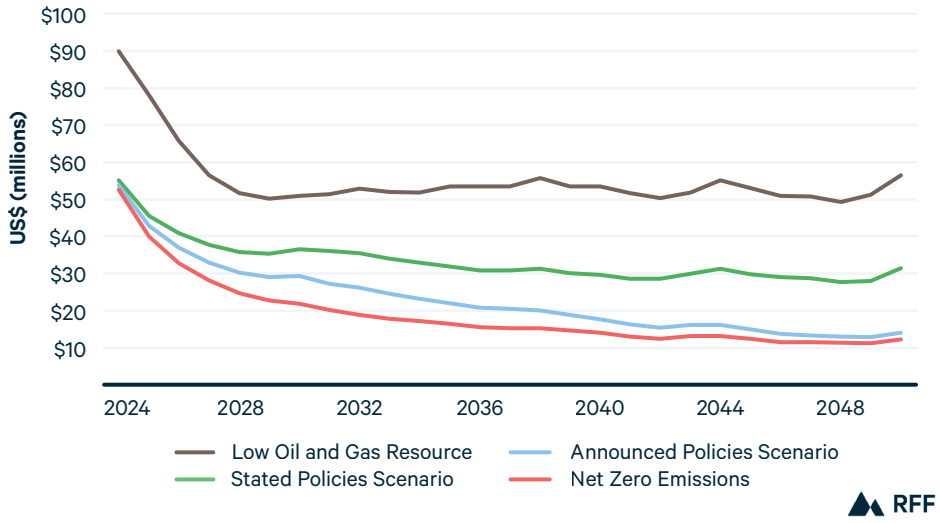
3.2. Oil and Gas Revenues

Next, we examine how changes in future oil and gas production affect Tribal revenue. As noted in Section 2.3, revenue projections include severance taxes applied to production from all wells across the Reservation, along with royalties from production on Tribal land. Data limitations mean that we are unable to project royalties flowing to individual tribal members or income generated by Tribal-owned businesses such as Red Willow and Red Cedar.

Unlike our projected results for future natural gas production, we find substantial variation in revenue generation across the four scenarios. This is mainly because royalties and severance taxes are based on the price of natural gas, which—by the end of the projection period—is three times higher under the LOG scenario than the NZE scenario. Under the LOG scenario, revenue initially declines because of rapidly falling production but then steadies in the range of $50 million to $60 million per year in the 2030s and 2040s. In the other scenarios, revenue also declines quickly in the first decade before steadying in the range of $10 million to $30 million per year, with the lowest revenue levels seen in the NZE scenario because of its low projected production and prices. Figure 3 illustrates these results.

9 Data and analysis based on authors' examination of data from Enverus, a proprietary source of oil and gas data and analytics.

Figure 3. Severance Tax and Royalty Revenue Across Four Modeled Scenarios

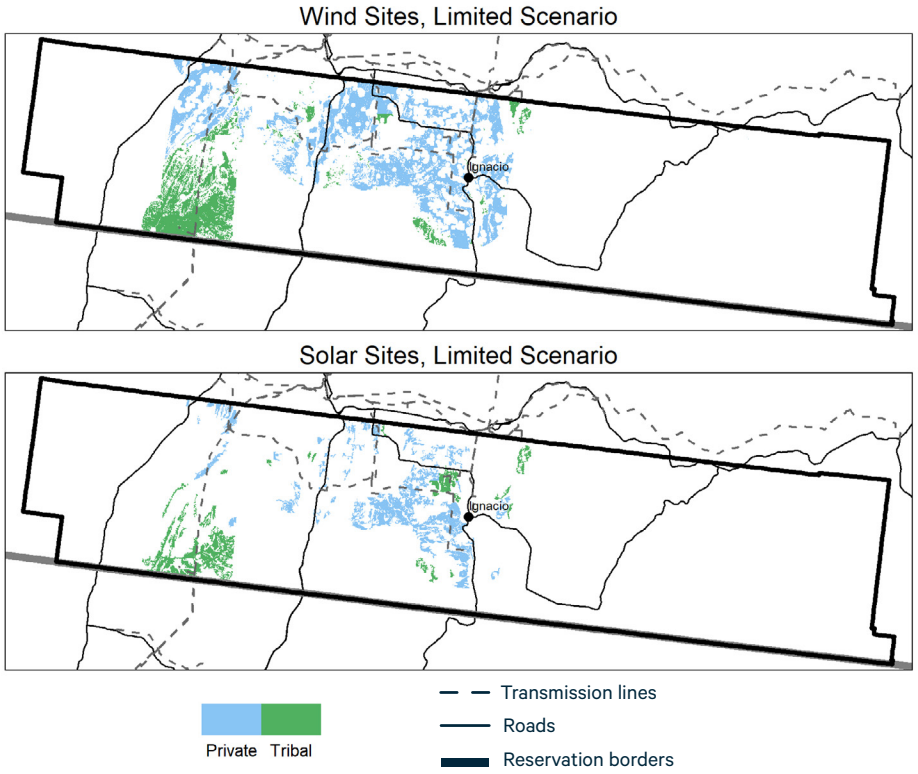


In net present value terms (assuming a discount rate of 10 percent), revenues between 2024 and 2050 are $244 million under the NZE scenario, $287 million under the APS, $355 million under the STEPS, and $566 million under the LOG. These wide ranges highlight the significance that future natural gas prices will hold for the public finances of the Tribe and its members. Unfortunately, broader information about the Tribe's budget is not publicly available, making it difficult for us to put these figures into context and understand how significant they are in supporting the government's operations.

3.3. Wind and Solar

Although wind and solar development is technically possible across a broad swath of the reservation, our analysis indicates that solar, but not wind, may be economically viable. We find that wind and solar could technically be developed across 1,376 km^2 and 1,091 km^2, respectively, of the Reservation (Figure 4), with between 31 and 47 percent of that land held collectively by the Tribe (most other lands suitable for wind and solar are privately owned). Under our Limited scenario, however, the amount of possible development declines dramatically, falling to 313 km^2 for wind (38 percent of which is tribally owned) and 137 km^2 for solar (43 percent of which is tribally owned).

Figure 4. Potential Wind and Solar Development Sites on the Reservation Under the Limited Scenario



Note: Only private and tribal lands are shown because no wind or solar development occurs on federally owned land within the reservation boundaries under the Limited scenario.

It is technically possible for wind to be developed across these large swaths of land, but wind resources on the Reservation are poor compared with those in other parts of the United States. We find that the average capacity factors for new wind projects on the reservation range from 16 to 19 percent across our three scenarios, compared with an average capacity factor of 44 percent for new onshore wind projected to be built in the United States (NREL 2023a). Similarly, we find that the LCOE for wind projects under the Limited scenario averages $89.30 per megawatt hour (MWh), far higher than the national average of $20.90 for projects projected to enter service in 2028 (EIA 2023c).[10] These low capacity factors and resulting high LCOEs limit the potential for wind projects to generate returns to potential investors, making it extremely unlikely that utility-scale wind development will be economically viable given current technologies and market conditions.

10 These LCOE figures include federal tax credits in place as of November 2024, as well as bonus credits for meeting domestic content requirements and, for projects on the SUIT reservation, qualifying for an additional "energy communities" tax credit. All figures are presented in 2023$. See Appendix C for details.

The story for utility-scale solar is quite different. We estimate that capacity factors for solar projects on the Reservation are roughly 32 percent across the three scenarios, near the high end of the range for existing and projected utility-scale projects in the United States (NREL 2023a). As a result, the LCOE for solar projects on the reservation averages $20.20/MWh under the Limited scenario, similar to the national average for projects projected to enter service in 2028 (EIA 2023c).

Under the Limited scenario, the potential capacity of solar generation on the Reservation is substantial, reaching 4.4 gigawatts. For reference, one large nuclear generator averages roughly 1 gigawatt of generating capacity. Although the Tribe has not pursued utility-scale solar development to date, our results clearly indicate that solar may be economically viable on parts of the Reservation.

4. Implications for Policy and Research

4.1. Policy implications

Throughout its history, the US federal government has failed to fully respect the sovereignty of Tribal Nations, including on issues related to energy development (Lawson 1982; Smith and Frehner 2010; Curley 2023; Raimi and Davicino 2024; Parker 2024). As the domestic and global energy system changes, Tribal Nations across the United States will face a range of challenges and opportunities regarding energy production on their lands. As these changes unfold, in many cases prompted by federal and state government laws and regulations, policymakers will need to consider the unique needs and wide range of capacities across the more than 500 Tribal Nations within the United States.

Some Tribal Nations, such as the Southern Ute Indian Tribe, have developed deep expertise and robust internal capacity to navigate a changing and uncertain energy landscape. Other fossil energy–producing nations, such as the Crow, Jicarilla-Apache, and Mandan-Hidatsa-Arikara—all substantial producers of fossil fuels—differ in their technical and financial capacity, suggesting that policymakers may need to provide tailored support to these nations if demand for coal, oil, and natural gas declines substantially in the years ahead. Some of these nations, such as the Crow, have already experienced substantial economic disruption as a result of declining coal demand, losing hundreds of local jobs and millions of dollars in annual revenues (Chaney 2024).

As we described in Section 3.3, one potential opportunity for the Southern Ute and other Tribes lies in renewable energy development. Recent analysis has found that the economic potential for wind and solar development on Tribal lands could reach into the tens of billions of dollars in the years ahead (Parker et al. 2024). However, development of renewable energy sources, just like fossil energy sources, will occur only with the majority consent of tribal members and their elected representatives. For the Southern Ute, and very likely for other tribes, energy development will be limited or prohibited on certain lands, and in some cases, it may be unwelcome altogether. For renewable energy development to occur at scale, land use planning and community involvement will be critical because of its visual and land use footprint.

In cases where renewable energy development is economically viable and desirable among Tribal members and leaders, it is unlikely to fully replace the high-paying jobs and substantial public revenues that are generated by coal, oil, and natural gas extraction (Raimi et al. 2024). Therefore, broader economic development strategies will likely be needed for Tribal Nations with high levels of dependence on fossil fuels for jobs and public revenue (Clarke et al. 2024). For Tribal leaders and economic development practitioners, substantial time, effort, and community engagement will be necessary to develop such strategies.

For federal and state policymakers seeking to support an equitable energy transition for Tribal Nations, a first step will be to understand the priorities and preferences of each tribe, which are far from monolithic. As David Lester, a former director of the Council of Energy Resource Tribes, has said, "If you've met one tribe…you've met one tribe" (DOE n.d.). Our work with the Tribe indicates that the culture, history, geography, politics, and natural resource endowments of each Tribal Nation will play a substantial role in determining which economic opportunities are most viable.

4.2. Implications for Researchers

Scholars across fields of public policy value the real-world impact that their research can have. In the case of energy policy, scholarship is needed to propose, model, and evaluate alternative policies that can help improve societal outcomes regarding energy access, affordability, security, and sustainability. In this research project, we have worked directly with the Tribe's policymakers to inform their decisionmaking regarding future energy development. During this process, we have learned several lessons that can benefit other scholars seeking to work with Tribal Nations in the United States (and perhaps other Indigenous groups).

First, we have learned that building relationships and trust is an essential component to an effective partnership. This is particularly important for Tribal Nations, who have been subjected to unethical research practices across a variety of domains (Saunkeah et al. 2021). Any research conducted in partnership with Tribal Nations will need to understand this history and, in rejecting these unethical practices, respect and defer to the inherent sovereignty of these nations. In practice, this means limits may be placed on the researchers in terms of the information they have access to and the information they can make public.

Second, we have learned that this relationship and trust building takes time and patience. Although researchers often face external pressures, such as publishing requirements for promotion, deadlines from funders, and other factors, these pressures must remain subservient to the requirements of the Tribal Nation if the collaboration is to be successful. This means that researchers (and funders), in many cases, will need to adjust their expectations about project timelines and outputs.

Third, we have learned that collaboration with Tribal Nations can be rewarding for both the research team and the Tribal partner. For the research team, access to the Tribe's experts has illuminated new areas that previously were poorly understood. For

example, the team learned some of the factors that inform the Tribe's decisionmaking with regard to investment in various energy and emissions-reduction technologies. The research team also learned nuances related to energy development on checkerboarded land, as Tribal tax policies vary depending in part on landownership classes.

For the Tribal partner, access to rigorous and independent analysis can support their decisionmaking in a variety of ways. For example, the Tribe's experts have told us that our oil and gas modeling results are largely consistent with their expectations, strengthening their views about future oil and gas investment. The Tribe's experts also told us that our modeled results for solar development were surprising and sparked further interest and that this work will support continued evaluation of solar development opportunities on the Reservation. This renewed interest is in accordance with the Tribe's "all of the above" energy development strategy.

Finally, our collaboration has taught us that data analysis without consultation with Tribal leaders and members has inherent limitations. Although rigorous empirical analyses can provide a useful guidepost for what is technically possible for Tribal energy development (e.g., Parker et al. 2024), such analyses do not account for the preferences of Tribal Nations, their members, or their elected leaders (Susskind et al. 2022). Our partnership with the Tribe, as well as less formal interactions with leaders and experts from other Tribal Nations, has made clear that understanding these preferences is essential for researchers and policymakers to ensure that Tribal sovereignty is fully respected.

5. Conclusions

Scholars and policymakers have increasingly called for energy policies that are "justice-aware" (Sovacool et al. 2017). One critical element of energy justice is ensuring that communities that rely heavily on fossil fuel extraction and related infrastructure can build viable and durable economies during and after an energy transition. This paper describes and presents the results of a multiyear collaboration between the research team and the Southern Ute Indian Tribe, a major natural gas–producing Tribal Nation in the United States. The collaboration offers one route through which scholars can help deliver a "just transition" for fossil fuel–producing Tribal Nations in the United States.

Key to the success of this collaboration has been a commitment to respect the inherent sovereignty of the Tribe. Other Tribal Nations in the United States (and Indigenous groups around the world), particularly those with substantial capacity limitations, could benefit from similar collaborations carried out by scholars with expertise in energy modeling, legal analysis, and other skills held widely across academia. Scholars, in turn, stand to benefit substantially from the expertise and unique perspectives held among members of Tribal Nations in the United States and Indigenous communities around the world.

The results of our modeling suggest that existing natural gas resources are likely to continue their recent declines, reducing revenue for the Tribe's government and its citizens. We also find substantial potential for economically viable solar energy development on the Reservation. As the domestic and global energy system continues to change, the Tribe is pursuing a raft of projects and investments, in energy and other sectors, that can help sustain government revenue and public benefits for decades to come.

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Appendix A: Methods for Estimating Southern Ute Indian Tribe Oil and Gas Production

A.1. Dynamic Oil and Gas Market Analysis (DOGMA) Model Overview

Our modeling of production in the San Juan Basin was based on a version of the Dynamic Oil and Gas Market Analysis (DOGMA) model. DOGMA separately models the drilling and completion of oil and gas wells and resulting monthly production for each class. Classes reflect the permutation of the jurisdictional areas (counties and reservations) and mineral ownership status (federal, state, tribal, or private). The model is based on well-level data on approximately 58,000 wells in the San Juan Basin, about 4,300 of which are on the reservation of the Southern Ute Indian Tribe (the Tribe). While most of the focus of the analysis is restricted to the Tribe, we use some data from the broader San Juan Basin to inform the analysis because of limited statistical power in some cases when focusing solely on data from the Southern Ute Indian Tribe's Reservation (the Reservation). The modeling approach closely tracks the one developed by Prest et al. (2024), which models drilling and production across five western oil and gas basins. While this documentation is adapted from the appendix of that paper, some modifications to that model have been made here, reflecting the focus on production on the Reservation and more granular mineral ownership data available in this project.

For each well, we identified mineral ownership by overlaying its surface hole's latitude and longitude with spatial data, including a confidential map of mineral ownership on the Reservation.[11] Wells with federally owned minerals were determined using spatial data from state BLM offices. State-owned minerals were determined similarly using spatial data from the state government agencies (Colorado State Land Board and New Mexico State Land Office). This resulted in 31 classes of wells across the San Juan Basin, including 6 classes on the Reservation reflecting the permutation of two counties (La Plata and Archuleta) and three types of mineral ownership (Tribal, fee/allotted, and federal). There is effectively zero oil production on the reservation, so our focus is gas production. There is relatively little allotted land, so we have combined fee and allotted land together into a single ownership category, and for concision, we refer to this category of mineral ownership simply as "fee." Existing gas production on the Reservation was about 0.55 billion cubic feet per day (bcf/d) in 2022, which is approximately split 60/40 percent between fee (0.34 bcf/d) and Tribal (0.19 bcf/d) ownership, with a very small amount (0.02 bcf/d) of federal production. The San Juan Basin as a whole produced about 2 bcf/d in 2022.

11 While in practice, horizontal well laterals can cross multiple ownership types, we do not generally have information on the laterals' paths. This limitation precludes us from estimating how much of the wellbore is passing through plots with different ownership structures. Thus we designate mineral ownership based simply on the surface hole.

Having categorized each well into one of the 31 classes, we model oil and gas production from each class in three stages: drilling, completion, and production over time. This appendix proceeds to describe the approach to each stage.

A.1.1. Modeling Drilling

The literature has demonstrated that of the three stages of oil and gas production—drilling, completion, and production over time—the drilling stage is the key price-responsive margin (Anderson et al. 2018; Newell et al. 2019; Newell and Prest 2019). DOGMA models dynamic oil- and gas-price elasticities of drilling supply using established methods from the literature (Newell et al. 2019; Newell and Prest 2019; Prest 2022). Equation (1) shows the model of drilling behavior, which reflects the elasticities of drilling activity in response to price fluctuations over time. While DOGMA normally includes oil prices as an independent variable in equation (1), the San Juan Basin is primarily a gas play; thus oil prices are omitted, since they are not expected to be a relevant driver.

$$\Delta log(WellsDrilled_t) = \sum_{l=0}^{12} \eta_{\ell}^{gas} \Delta log(\text{GasPrice}_{t-\ell}) + \lambda_{moy} + \varepsilon_t \quad (1)$$

As in the literature (e.g., Prest et al. 2024), $WellsDrilled_t$ reflects Henry Hub gas prices. Equation (1) is estimated by ordinary least squares using historical data with Newey-West standard errors, yielding dynamic elasticities in response to changes in gas prices, denoted as η_{ℓ}^{gas} for lag order $\ell \in \{0, 1, \ldots, 12\}$.[12]

The long-run drilling elasticity is given by the cumulative sum $\overline{\eta^{gas}} = \sum_{\ell=0}^{12} \eta^{gas}$.

We estimate equation (1) one time for the entire San Juan Basin, rather than for each of the 31 classes, because of the small number of observations for some classes with little development, resulting in low statistical power. The basin-level regression allows for greater precision, at the cost of assuming uniform elasticities for all classes within a basin. The estimated cumulative elasticity is 0.93 (standard error 0.46, p = 0.045), roughly consistent with findings in the literature.[13]

For each class, drilling is projected based on average monthly drilling levels (wells per month) for that class during a baseline benchmark period of 2017–23, adjusted dynamically into the future using the elasticities from equation (1) applied to alternative trajectories of gas prices. Compared with Prest et al. (2024), we expanded the baseline period from a single year to this seven-year period to account for the sporadic nature of drilling activity in some class categories. For instance, in some well classes, no wells were drilled in 2021, even though wells were nonetheless drilled in

12 The historical data are 385 monthly observations from January 1992 to December 2023.

13 We also estimated equation (1) using only wells drilled on the Reservation. The relatively small number of wells drilled on the reservation resulted in noisy time series of drilling activity and hence less power. The estimated elasticity was a positive statistically insignificant 0.48 (standard error 0.47, p = 0.30).

other years, such as 2022. An important example of this is the category of wells on the Reservation with Tribal minerals. Basing future drilling activity entirely on the 2021 experience would result in zero projected drilling activity in a region where drilling is in fact occurring, albeit sporadically.

We use the price trajectories from the International Energy Agency's *World Energy Outlook 2023* (IEA 2023). It features three scenarios: in order of increasingly ambitious global decarbonization, the Stated Policies Scenario (STEPS), Announced Pledges Scenario (APS), and Net Zero Emissions (NZE). All these scenarios feature relatively low Henry Hub prices, which in 2030 reach $4.00 (STEPS), $3.20 (APS), or $2.40 (NZE) per million British thermal unit (MMBtu). We therefore also include the Low Oil and Gas Resource scenario from the *Annual Energy Outlook 2023* (EIA 2023), which has gas prices reaching about $5/MMBtu in 2030 and exceeding $6/MMBtu in 2050. In all cases, we interpolate the price trajectories to the monthly level and use the estimated and η^{gas} coefficients from equation (1) to generate pathways of newly drilled wells for each class j and month t, denoted as $d_{t,j}$, that evolve based on the basin-level elasticities starting from baseline average rate of wells drilled per month, by class.

A.1.2. Modeling the Completion of Newly Drilled Wells

The drilling model discussed in the previous section produces trajectories of drilling activity—that is, an estimated number of wells drilled of each class j in each month t, which we denote as $d_{t,j}$. Because it takes time to drill and complete a well, a time lag occurs between drilling commencement and production. We convert wells drilled, $d_{t,j}$, to newly producing wells in each period, denoted as $w_{t,j}$, using the distribution of the number of months it takes between drilling commencement and production. We denote the share of wells coming online ℓ months after drilling commenced as s_ℓ. The relationship between wells drilled $d_{t,j}$ and newly producing wells $w_{t,j}$ is given by

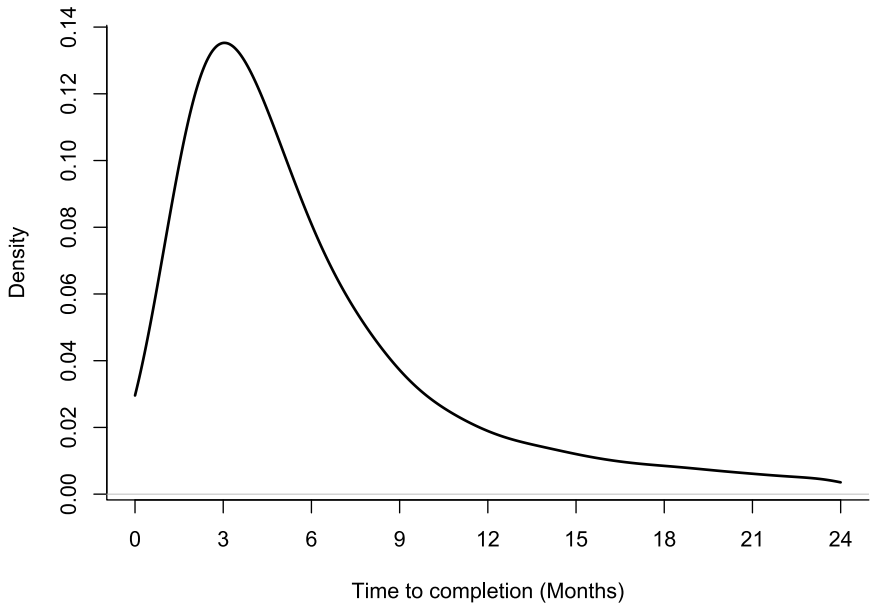
$$\mathrm{w}_{j,t} = \sum_{\ell=0}^{24} \mathrm{d}_{j,t-\ell}\mathrm{s}_\ell \qquad (2)$$

We estimate the distributions of drill-to-production time, s_ℓ, using the empirical distributions of these values among wells that came online in or after 2011 (see Figure A.1), to reflect the changing nature of completion times driven by the shale boom. We use basin-wide average values, rather than well-class-specific ones, because of the small number of wells in some class categories that would produce noisy estimates of $s_{b,\ell}$ if it were calculated at the class (j) level. As did Newell et al. (2019), Newell and Prest (2019), and Prest et al. (2024), we include wells with reported completion times of 24 months or less, which accounts for most wells.[14] We additionally discretize the resulting $w_{j,t}$ estimate to reflect that wells are discrete objects.[15]

14 Longer reported times are often due to data errors.

15 We discretize $w_{j,t}$ by taking its the integer component and adding one well at random with a probability equal to its decimal component. For example, if $w_{j,t} = 1.33$ for a given class j and month t, the discretized number of newly drilled wells would be 1 with 67 percent probability and 2 with 33 percent probability.

Figure A.1. Distributions of completion time, by basin



Note: Density reflects relative frequency, or likelihood.

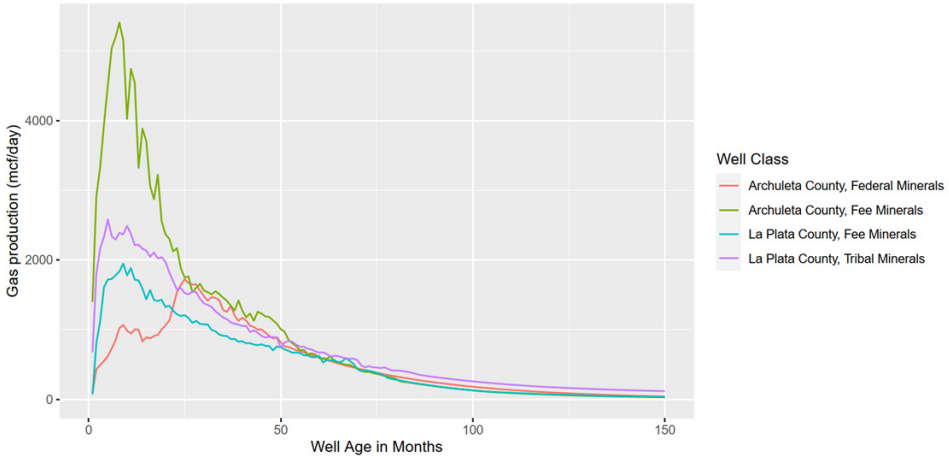
A.1.3. Modeling Production from Newly Drilled Wells

The trajectories of newly producing wells convert into production over time. Each well i of class j produces oil and gas each month (t), denoted as $\mathrm{q}_{i,j,t}^{oil}$ and gas $\mathrm{q}_{i,j,t}^{gas}$. Well i's production profile—often called a type curve—is assumed to follow a shape equal to the average type curves for oil and gas production among wells in its class that came online in the same benchmark baseline period of 2017–23. As discussed in the next section, we extend production profiles of existing wells that were still producing as of 2023 out into the future using well-specific Arps projections. Thus the average type curve beyond the observed history (for example, beyond seven years of production for a well that came online in 2017) reflects the average of these well-specific Arps projections. The resulting type curves are then normalized to the average initial productivity (IP) rate of that well class during the 2017–23 benchmark period. The resulting production profiles for wells on the Reservation are shown in Figure A.2.

This approach represents two simplifications relative to the methods used by Prest et al. (2024). First, that paper randomly sampled IP rates in the forward-looking simulation to reflect uncertainty in future IP values. That approach has little effect on the central estimates of projected production, and thus we drop it here for simplicity. We also considered using the same methods as Prest et al. (2024) to model the high-grading effect, which reflects how IP can decline as more wells are drilled and marginally lower-quality reserves are tapped. However, there was no clear empirical evidence for high grading on the Reservation, with a very small estimated relationship of the wrong sign (i.e., positive, at +4 mcf/day (p = 0.01) for each other well drilled within the same month). Thus we omit this here, although including it has little meaningful effect on the results.[16]

16 We also found a very small time trend of approximately +17 mcf/d per year in well IP ($p<0.001$), which we also exclude, but including it has little effect.

Figure A.2. Type Curves for Gas Production on SUIT Reservation



Note: Only well classes with positive drilling activity on SUIT in the 2017–23 baseline period are shown. Oil production profiles are not shown because oil production on the reservation is effectively zero.

A.1.4. Modeling Production from Existing Wells

While the methods described in Sections A.1.1–A.1.3 pertain to modeling production from newly drilled wells, some production is expected to continue from the approximately 30,000 wells still active as of 2023. Oil and gas production is projected forward for each such well using well-level Arps curves, as is common practice in petroleum engineering. This equation, describing the evolution of well i's production of product $p \in \{oil, gas\}$ in period t, is described in equation (3):

$$\mathrm{q}^{p}_{i,j,t} = \frac{\mathrm{c}_i}{1 + \mathrm{b}_i \mathrm{a}_i (\mathrm{WellAge}_{\mathrm{i,t}})^{1/\mathrm{b}_i}} + \in_{i,t} \qquad (3)$$

The Arps curve's parameters, including initial flow rate c_i, initial decline rate a_i, and curvature b_i, are all estimated at the well level via nonlinear least squares and projected forward based on the resulting shape, normalized to the well's last observed level of production. In some instances, the nonlinear estimation of equation (3) fails to converge or produces nonsensical parameter values. In either case, we simply impose an exogenous 3 percent monthly decline rate, which approximates a typical long-run monthly decline rate. For cases where the Arps fit fails to converge, we impose the 3 percent decline rate starting after the last observed production date. For cases where the Arps fit implies increasing production beyond some point, we impose the 3 percent decline rate starting at the point where the Arps curve would otherwise begin to slope upward.

A.1.5. Aggregation

The previous subsections result in well-level production from both existing and new (simulated) wells, $q_{i,j,t}^{oil}$ and $q_{i,j,t}^{gas}$. These production values can be aggregated to the class (j) level or higher (e.g., by ownership type) as appropriate through simple summation.

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Appendix B: Methods for Estimating Oil and Gas Revenue for the Southern Ute Indian Tribe

To estimate the value of oil and natural gas production on the Reservation, we take future natural gas prices (in $/MMBtu) using Henry Hub pricing assumptions from IEA and EIA.[17] We take oil prices (in $/bbl) from the same.[18] We convert modeled natural gas production from volumetric units (mcf) to energy units (MMBtu) assuming a heat content of 0.977 MMBtu per mcf of natural gas.[19] We multiply the volume of production by the value of each commodity to estimate the gross value of production in each year during the modeling period.

To estimate royalty revenues, we apply the relevant rate (rising linearly from 12.5 percent in 2022 to 16.67 percent in 2032) to the gross value of production from all parcels where the Tribe owns the minerals. To estimate severance tax revenues, we multiply the tax rate (6.5 percent) by the gross value of production minus the deductions described below.

Severance tax is 6.5 percent and is paid on the same value as royalties, with several exemptions outlined in the Tribe's severance tax code (Section 21-2-104). Those exemptions are as follows:

- royalties paid to the tribe or an Indian allottee mineral owner,
- on-lease use; and,
- cross-lease beneficial use.

Based on an internal communication with the Tribe, these deductions reduce the value of production subject to severance tax by roughly 20 percent relative to total gross value. When we deduct royalties paid to the Tribe from severance tax liability, this implies that 8 percent of the gross value of production was used for on-site or cross-lease beneficial use.

17 Most operators on the Reservation pay royalties and severance taxes based on the San Juan Basin Indian Index price, which is calculated using a complex formula including a deduction for transportation costs. We use projected Henry Hub prices to estimate future production and revenue for two main reasons. First, there is no publicly available source that projects future prices for the San Juan Basin Indian Index price. Second, when we examine historical data, these two prices are typically quite similar, with no consistent pattern that would enable us to confidently estimate whether future San Juan Basin Indian Index prices would be higher or lower than future Henry Hub prices.

18 As noted in the main text, oil production is very small but greater than zero.

19 This figure was provided by the Tribe in July 2024.

Appendix C: Methods for Estimating Potential Wind and Solar Generation

The goal of this modeling exercise is to evaluate generation potential on the Southern Ute Indian Tribe Reservation of possible utility-scale photovoltaic (PV) and wind sites under alternative land use and infrastructure connection constraint scenarios. Specifically, we carry out four distinct phases of analysis:

- quantify technically viable generation potential
- quantify how various scales of land use restrictions affect generation potential
- examine the spatial relationships between potential sites and key infrastructure (e.g., transmission lines)
- estimate the economic potential of new utility-scale solar or wind projects

We estimated the total potential wind and solar energy generation based on land use following methods established by the National Renewable Energy Laboratory (NREL) (Milbrandt et al. 2018). These uses have resource requirements (sufficient sunshine and wind speeds) and physical constraints (such as slope). In addition, these uses (particularly solar power because of its relative area requirements) present opportunity costs in terms of land use trade-offs. Using a suite of geospatial data and technical specifications, we created hypothetical sites that could be developed for these renewable energy projects.

Importantly, this analysis does not integrate site-level feasibility and environmental studies, some of which are required by law. Therefore, this analysis is intended to demonstrate in broad terms how land use trade-offs interact with the potential for solar and wind renewable energy development on the Reservation.

C.1. Methods

We developed a custom and highly spatially resolved model by following and adapting methodology from NREL and peer-reviewed literature. The model incorporates land use constraints and identifies potential sites for solar and wind projects according to custom site parameters. It calculates the technical potential for electricity generation and levelized cost of energy (LCOE) for each site. In all phases of processing and analysis, we developed reproducible code using Python (including the *arcpy* package) and R/RStudio (including the *sf*, *terra*, *tigris*, and *tidyverse packages*).[20] The model has been structured so that parameters (e.g., land use constraints, site minimum area, power density, technological development scenario) can be modified to evaluate alternative scenarios.

20 During the preparation of this work, coauthor Thompson used the artificial intelligence tools ChatGPT and Gemini to assist in the development of data-processing code.

C.1.1. Creating Three Scenarios

Both solar and wind energy projects are highly dependent on terrain and land use characteristics. We identified those characteristics from the literature and associated high-resolution spatial data. Many site limitations are well documented and used in similar studies (e.g., Milbrandt et al. 2018; Lopez et al. 2021; Doris et al. 2013; Grue et al. 2021). It is useful to evaluate a range of possible development scenarios to examine the effects of specific constraints on the location and extent of potential sites. Following this literature, we present results under three development scenarios: (1) technical, which represents the maximum build-out and is limited primarily by physical constraints; (2) reference, which incorporates some basic real-world constraints (e.g., critical wildlife habitat sites are excluded); and (3) limited, which is more restrictive and considers additional land use protections or infrastructure requirements (e.g., prime farmland sites are excluded and larger buffers are given to water bodies).

Importantly, these scenarios do not include constraints related to cultural, religious, and archaeological sites of the Reservation. We respect the rights and authority of the Tribal community as owners and stewards of this sensitive information. Accordingly, we wish to acknowledge that the results of our build-out scenarios may include potential sites within these areas.

Table C1 presents each constraint by category (physical landscape, environment, land use, and administrative) and the associated development scenario to which it is applied. Most development constraints were derived from the literature on renewable energy site development (e.g., Milbrandt et al. 2018; Lopez et al. 2021). References and spatial data sources for each constraint are listed in Table C2.

Table C.1. Scenario Constraints

Category	Layer	Exclusion	Technology and Scenario					
			Solar			Wind		
			Technical	Reference	Limited	Technical	Reference	Limited
Physical Landscape	Slope	>10%	X	X	X			
		>20%	X	X	X	X	X	X
	High Mountanis	Elevation >2,743 meters	X	X	X	X	X	X
	Water Bodies and Wetlands	All	X	X	X	X	X	X
Environment	Water Bodies and Wetlands	Within 30 meter Buffer		X	X			
		Within 300 meter Buffer			X	X	X	X
	Areas of Unprotected Biodiversity Importance	All			X			X
Land Use	Built-up Areas	All	X	X	X	X	X	X
	Airports	All	X	X	X	X	X	X
	Transmission Lines	Outside 20 kilometer Buffer		X	X		X	X
		Outside 5 kilometer Buffer			X			X
	Forests	All			X			X
	Agriculture (Crops and Pasture)	All			X			
	Prime Farmland Soil	All			X			
Administrative	Fish and Wildlife Services Critical Habitat Area	All		X	X		X	X
	Federal Lands	All			X			X

Table C.2. Individual Constraint Data Sources and Exclusion References

Category	Layer	Exclusion	Data Source	Exclusion Reference
Physical Landscape	Slope	>10%	(Rubino 2011)	(Milbrandt et al. 2018; Mooney et al. 2021; Wu et al. 2023)
		>20%		
	High Mountanis	Elevation >2,743 meters	(Esri 2022)	(Lopez et al. 2021)
	Water Bodies and Wetlands	All	(Dewitz and USGS 2021)	(Milbrandt et al. 2018)
Environment	Water Bodies and Wetlands	Within 30 meter Buffer		(Hise et al. 2022; Sweeney and Newbold 2014; Lopez et al. 2021)
		Within 300 meter Buffer		
	Areas of Unprotected Biodiversity Importance	All	(NatureServe Network 2021)	
Land Use	Built-up Areas	All	(Pesaresi and Politis 2022)	(Milbrandt et al. 2018)
	Airports	All	(Esri 2017)	(Milbrandt et al. 2018)
	Transmission Lines	Outside 20 kilometer Buffer	(DHS GMO 2022)	
		Outside 5 kilometer Buffer		
	Forests	All	(Dewitz and USGS 2021)	
	Agriculture (Crops and Pasture)	All		
	Prime Farmland Soil	All	(ESRI and NRCS 2017)	
Administrative	Fish and Wildlife Services Critical Habitat Area	All	(FWS 2023)	(Wu et al. 2015; DOI and DOE 2012)
	Federal Lands	All	(Esri 2018)	(Milbrandt et al. 2018)

The technical scenario identifies all feasible sites under the minimum requirements and with as few development limitations as possible. Constraints include physical limitations to development (e.g., slope, water/wetland features, and built-up areas). The reference scenario represents a more realistic set of constraints, including those identified in the technical case plus minimal environmental protections (e.g., 30-meter buffers around water and wetland features), areas within 20 km of existing transmission lines, and critical habitat area.

The limited scenario includes these constraints plus higher standards for environmental protection, land use considerations, and distance to existing infrastructure. Larger buffers around water features and wetlands are incorporated into this scenario to protect water and habitat quality (Hise et al. 2022; Sweeney and Newbold 2014; Lopez et al. 2021). Forests and areas of unprotected biodiversity importance are excluded in this scenario (NatureServe Network 2021; Hamilton et al. 2022), as they are important habitats for imperiled species.[21]

Whereas wind turbine projects can often be co-sited with existing agriculture, PV panels present greater opportunity costs in terms of land use. Consequently, we exclude both current agriculture and potentially high-yielding lands (areas with prime farmland soil) from potential PV projects in the most limited development scenario.

C.1.2. Creating Sites

All spatial data are converted to 30 meter binary rasters and aligned with the National Land Cover Database layer (Dewitz and USGS 2021). Raster cells are assigned a value of one if they meet the development criterion (i.e., can be developed) and assigned a value of zero otherwise. For example, all cells with slope values exceeding 20 percent are given a value of zero. The product of all rasters relevant to each scenario results in a raster with a cell value of one for suitable land, representing the developable land for that case (zero otherwise).

Using the binary rasters for three scenarios and two technologies, we create sites by identifying contiguous areas of suitable cells (e.g., Milbrandt et al. 2018; Lopez et al. 2012; Doris et al. 2013; Grue et al. 2021; Singer 2020; Wu et al. 2015). Those contiguous areas are converted to polygons. Minimum and maximum site areas are then applied. For solar sites, the minimum area for a viable site is set at 0.2 km^2 (about 50 acres); the maximum area for a single site is set at 3.125 km^2, which is the area that could support a 100-megawatt (MW) capacity project assuming a power density of 32 MW/km^2 (Grue et al. 2021). For wind sites, the minimum site area is set at 0.008 km^2 (2 acres), and the maximum site area, supporting 100 MW assuming a power density of 3 MW/km^2, is 33 km^2 (Lopez et al. 2021). Potential wind sites can be significantly larger than solar sites because of the ability to co-site them with other land uses, such as agriculture.

21 The data on areas of unprotected biodiversity importance encompass species with global conservation ranks of critically imperiled (G1) or imperiled (G2), plus any species listed under the Endangered Species Act as threatened or endangered (Hamilton et al. 2022).

Polygons smaller than the minimum site area are dropped, while those larger than the maximum are split into smaller sites. Specifically, each large site is split into quadrants; resulting polygons, if still larger than the maximum allowable area, are split into quadrants again, and so on (Grue et al. 2021). Isolated fragments smaller than the minimum area are removed. Because of the process that splits sites, some have a rectangular shape.[22] The resulting polygons are the sites we use to analyze technical potential and levelized cost of energy. In addition, we calculate the minimum distance (i.e., from the edge of the polygon) from each site to the nearest transmission line. In practice, developers could build across multiple sites to create larger projects if desired.

C.1.3. Assessing Technical Potential

For each site, we calculate the technical potential electric capacity and generation. Technical potential capacity (MW) is the maximum possible installed capacity given current technology (power density), land area, and efficiency of the technology given local wind or solar resources (capacity factor). Technical potential generation (MW/year) is the associated maximum possible generation over a year.

Power density (MW/square kilometer) is the amount of power per unit area that can be generated by a specific technology. This ratio is used to calculate the potential generation output of a particular technology. We use power densities of 32 MW per square kilometer for PV and 3 MW per square kilometer for wind (Grue et al. 2021; Lopez et al. 2021).

Capacity factor is the ratio of actual energy output to the maximum possible energy output over a given time period. In this case, the main variable affecting capacity factor is local resource availability: sunlight and wind resources in the area of the potential site. Higher gross capacity factor values indicate greater resource availability and vice versa. Net capacity factors integrate system losses resulting from variability in resource utilization due to maintenance, downtime, grid demand, and other factors. Over time, capacity factors will increase as technology improves, so projects built in future years would likely have higher capacity factors than those used in this modeling exercise.

We use NREL's 2023 wind and solar supply curve data to identify the capacity factor for each site (NREL 2023a, b). The supply curves simulate potential sites across the United States at a resolution of 11.5 km. The capacity factors in the supply curve data are associated with NREL's "moderate" Annual Technology Baseline scenario. There are three sets of supply curve sites representing alternative land use restriction scenarios: open access, reference access, and limited access. The open access scenario includes the greatest number of sites and effective spatial resolution, so we use data for those

22 Resulting polygons are simplified (with a tolerance of 5 meters) to straighten out boundaries created by 30 meter raster cells.

scenarios.[23] For each of our sites, we identify the nearest NREL supply curve site and take its capacity factor value.[24]

Equations for technical potential capacity and generation are as follows, adapted from NREL (Doris et al. 2013):

Equation for technical potential capacity

$$\mathrm{cap}_{it} = \mathrm{A}_i \cdot \mathrm{PD}_t$$

where

i = potential site

t = technology

cap_{it} = technical potential capacity in site i for technology t (MW)

A_i = area of site i (km^2)

PD_t = power density of technology t

Equation for technical potential generation

$$\mathrm{gen}_{it} = \mathrm{cap}_{it} \cdot \mathrm{CF}_{it} \cdot 8,760 hour/year$$

where

gen_i = technical potential annual generation in site i (MWh)

CF = capacity factor at site i for technology t (percent)

5.1.4. Calculating Levelized Cost of Electricity

To assess the potential economic viability of building wind or solar at each site, we calculate the LCOE. The LCOE is used to evaluate the economic viability of an energy generation project, expressed in per-kilowatt cost of building and operating the energy plant over its lifetime. Note that we assume project developers are non-Tribal entities and are thus subject to federal and state income taxes. The LCOE of solar and wind projects is calculated with the following equation (NREL 2024a):

23 As of July 25, 2024, data for the solar open access supply curve scenario were unavailable, so we use sites from the reference access scenario in this study. Inspecting the subsequent release of the open access supply curve scenario sites in our area of interest reveals the same number of sites in both scenarios and no significant difference in capacity factors.

24 Both direct current (DC) and alternating current (AC) capacity factors are available for solar supply curve sites. We take the AC value to allow for integration with the NREL 2024 Annual Technology Baseline, which represents PV metrics in terms of AC kilowatts (see **https://atb.nrel.gov/electricity/2024/utility-scale_pv**).

Equation for site levelized cost of energy

$$\mathrm{LCOE}_{it} = ((CRF_t \cdot ProFinFactor_t \cdot (OCC_t \cdot CapRegMult + GCC_t) + FOM_t) \cdot 1,000/(\mathrm{CF}_{it} \cdot 8,760)) + VOM_t - PTC_t$$

where

LCOE_{it} = *levelized cost of energy for technology* t *at site* i *(US$/MWh)*

CRF_t = *capital recovery factor of technology* t

$ProFinFactor_t$ = *project finance factor for technology* t

$CoFinFactor_t$ = *construction finance factor for technology* t[25]

OCC_t = *overnight capital cost for technology* t *(US$/kW)*

$CapRegMult$ = *capital regional multiplier*[26]

GCC_t = *grid connection costs for technology* t *(US$/kW)*

FOM_t = *fixed operation and maintenance expenses for technology* t *(US$/kW-year)*

VOM_t = *variable operation and maintenance expenses for technology* t *(US$/kW-year)*[27]

PTC_t = *production tax credit for technology* t *(US$)*

As shown, a wide range of technical and economic factors constitute the LCOE. These include site-level characteristics such as capacity factor and resource availability, as well as conditions of technology, costs, policy, and research and development trajectories. For this set of terms, we leveraged NREL's latest "Annual Technology Baseline" (ATB) for information on utility-scale PV and land-based wind (NREL 2024a). Parameters that are constant across all potential sites are presented in Table C3.

Because the methodology in the capacity factor data source uses the moderate technology innovation scenario, we use the ATB terms associated with the same case.[28] We also use values projected to 2025, a cost recovery period of 30 years, and the market financial scenario (in contrast with the research and development scenario). The cost recovery period is the time it takes to recoup the initial capital investment required to build a plant and is set at 30 years to reflect the typical operational lifespan of renewable energy infrastructure (NREL 2024a).

In addition to these parameters, metrics vary depending on the resource class of the site. Resource class represents the availability of the relevant energy source at the

25 The production finance factor includes a term for combined federal and state tax rate. The 2024 NREL ATB sets the tax rate equal to 25.7 percent.

26 Because we are not comparing across regions, we set the capital regional multiplier equal to one.

27 The NREL (2024a) reports variable operation and maintenance expenses to be zero for both utility solar and land-based wind projects.

28 Descriptions of the moderate technology innovation scenarios for wind and solar can be viewed at **https://atb.nrel.gov/electricity/2024/utility-scale_pv and https://atb.nrel.gov/electricity/2024/land-based_wind**.

site location (i.e., sunshine and wind speeds). To approximate the resource class of each site, we take the nearest value from the spatial data on solar irradiance and wind speeds from NREL solar and wind supply curves (NREL 2023a, b) and link those values to resource class using the crosswalk tables on the NREL ATB solar and wind websites (NREL 2024a).

Table C.3. 2024 ATB Parameter Site-level Statistics (For Market Case and Year 2025)

		Technology and Scenario					
		Solar			Wind		
	Statistic	Technical	Reference	Limited	Technical	Reference	Limited
ATB fixed operating maintenance costs (US$/kW-year)	Minimum	21.0	21.0	21.0	31.2	31.2	31.2
	Maximum	21.0	21.0	21.0	40.0	40.0	31.2
	Mean	21.0	21.0	21.0	31.3	31.3	31.2
	Standard deviation	0	0	0	0.7	0.7	0
ATB overnight capital costs (US$/kW)	Minimum	1,323.1	1,323.1	1,323.1	1,466.5	1,466.5	1,929.2
	Maximum	1,323.1	1,323.1	1,323.1	1,929.2	1,929.1	1,929.2
	Mean	1,323.1	1,323.1	1,323.1	1,926.4	1,925.9	1,929.2
	Standard deviation	0	0	0	35.6	38.3	0
ATB captial recovery factor	All values	0.6	0.6	0.6	0.1	0.1	0.1
ATB project financing factor		1.0	1.0	1.0	1.1	1.1	1.1
ATB variable operation maintenance costs (US$/kW-year)		0	0	0	0	0	0
ATB capital regional multiplier		1	1	1	1	1	1

C.1.5. Subsidies under the Inflation Reduction Act

We incorporate the production tax credit (PTC) as specified by the Inflation Reduction Act (2022) into the calculation of the LCOE by following the equation provided in the ATB (NREL 2024a, b). The PTC is available for 10 years, so the PTC equation includes a term for adjusting the value to the full cost recovery period used to calculate the LCOE (30 years):

Equation for site production tax credit

$$\mathrm{PTC}_t = \frac{\mathrm{PTC}_{full}}{1 - TR} \times \frac{CRF}{\mathrm{CRF}_{10years}}$$

where

PTC_t = value of production tax credit to be subtracted from the LCOE (US$/MWh) for technology t

PTC_{full} = full value of production tax credit (US$/MWh)

TR = tax rate

CRF = capital recovery factor

$\mathrm{CRF}_{10years}$ = 10-year CRF relative to the full CRF of the project

Parameter values are presented in Table C3. We used the NREL ATB default combined federal and state tax rate of 25.7 percent. We assumed that projects will meet the Treasury Department's labor and wage requirements to receive the base credit of $27.50/MWh (DOE 2024). We identified whether potential sites would be eligible for the energy communities bonus using spatial data from the US Department of Energy (DOE, NETL, IWG, and DOT 2023).

C.2. Results

C.2.1. Locations for Potential Development

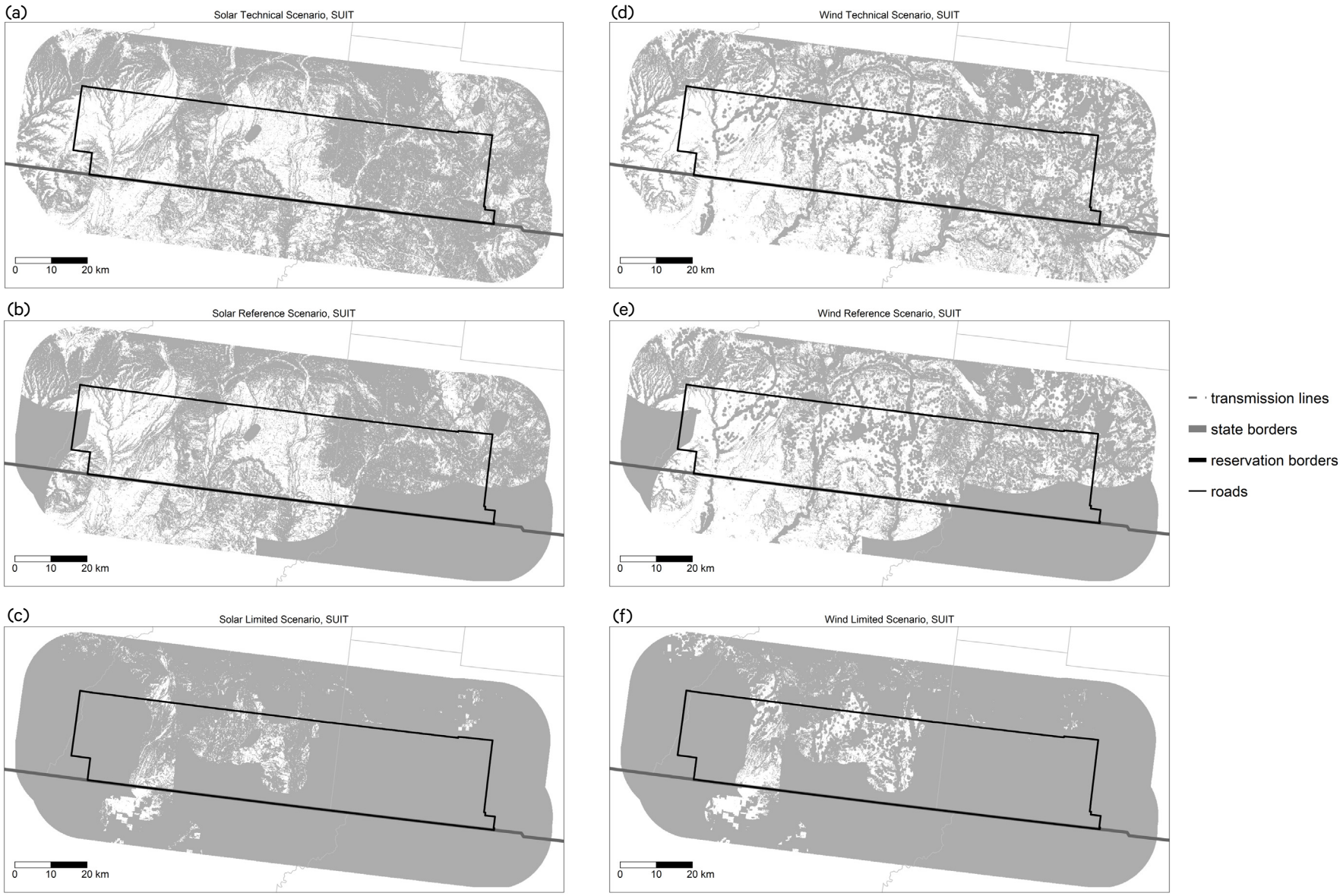
Our results reveal wide variation in the potential for wind and solar development across the different scenarios. Wind development is technically possible on 51 percent of reservation land (roughly 1,400 km^2), but this figure drops to 46 percent (~1,300 km^2) under the reference scenario and just 12 percent (~300 km^2) under the limited scenario. Solar is technically viable across 46 percent (~1,300 km^2) of reservation land, declining to 41 percent (1,100 km^2) and 7 percent (200 km^2) under the reference and limited scenarios, respectively.

The largest technical barrier to development is slope, which prevents development on 50 percent of the reservation for solar and 30 percent for wind. Table C4 presents area impacts of all individual constraints. Under the reference scenario, roughly 12 percent of technically developable locations are eliminated because they are not within 20 km of a transmission line. Under the limited scenario, proximity to transmission again is the largest factor, reducing potential development by 68 percent because these locations are not within 5 km of a transmission line. Figure C1 illustrates these results.

Table C.4. Area and Percentage of Area Identified as Off-limits by Individual Exclusion Scenarios

Category	Layer	Exclusion	Percentage of the Reservation Excluded	Area of the Reservation Excluded (km^2)
Physical Landscape	Slope	>10%	51.13	1,409
		>20%	28.76	793
	High Mountanis	Elevation >2,743 meters	0.10	3
	Water Bodies and Wetlands	All	2.04	56
Environment	Water Bodies and Wetlands	Within 30 meter Buffer	4.37	120
		Within 300 meter Buffer	25.43	701
	Areas of Unprotected Biodiversity Importance	All	22.69	625
Land Use	Built-up Areas	All	0.83	23
	Airports	All	0.73	20
	Transmission Lines	Outside 20 kilometer Buffer	11.51	317
		Outside 5 kilometer Buffer	67.89	1,871
	Forests	All	39.55	1,090
	Agriculture (Crops and Pasture)	All	9.53	263
	Prime Farmland Soil	All	17.23	475
Administrative	Fish and Wildlife Services Critical Habitat Area	All	0.04	1
	Federal Lands	All	9.03	249

Figure C.1. Land Use Scenario Constraint Maps



C.2.2. Potential Development Sites

The disparity between land available for solar and wind under all scenarios increases further after creating discrete sites. Under the technical (least restrictive) scenario, almost 3,000 distinct potential wind sites cover about 1,400 km^2, compared with roughly 1,000 potential solar sites covering 1,100 km^2 (Table C5). Under the limited (most restrictive) scenario, there are nearly 700 potential wind sites covering 313 km^2 and about 150 solar sites covering nearly 140 km^2. The locations of sites under each scenario are presented in the panel of maps in Figure C2 (for solar) and Figure C3 (for wind). Site-level statistics of area and distance to transmission line are presented in Table C6.

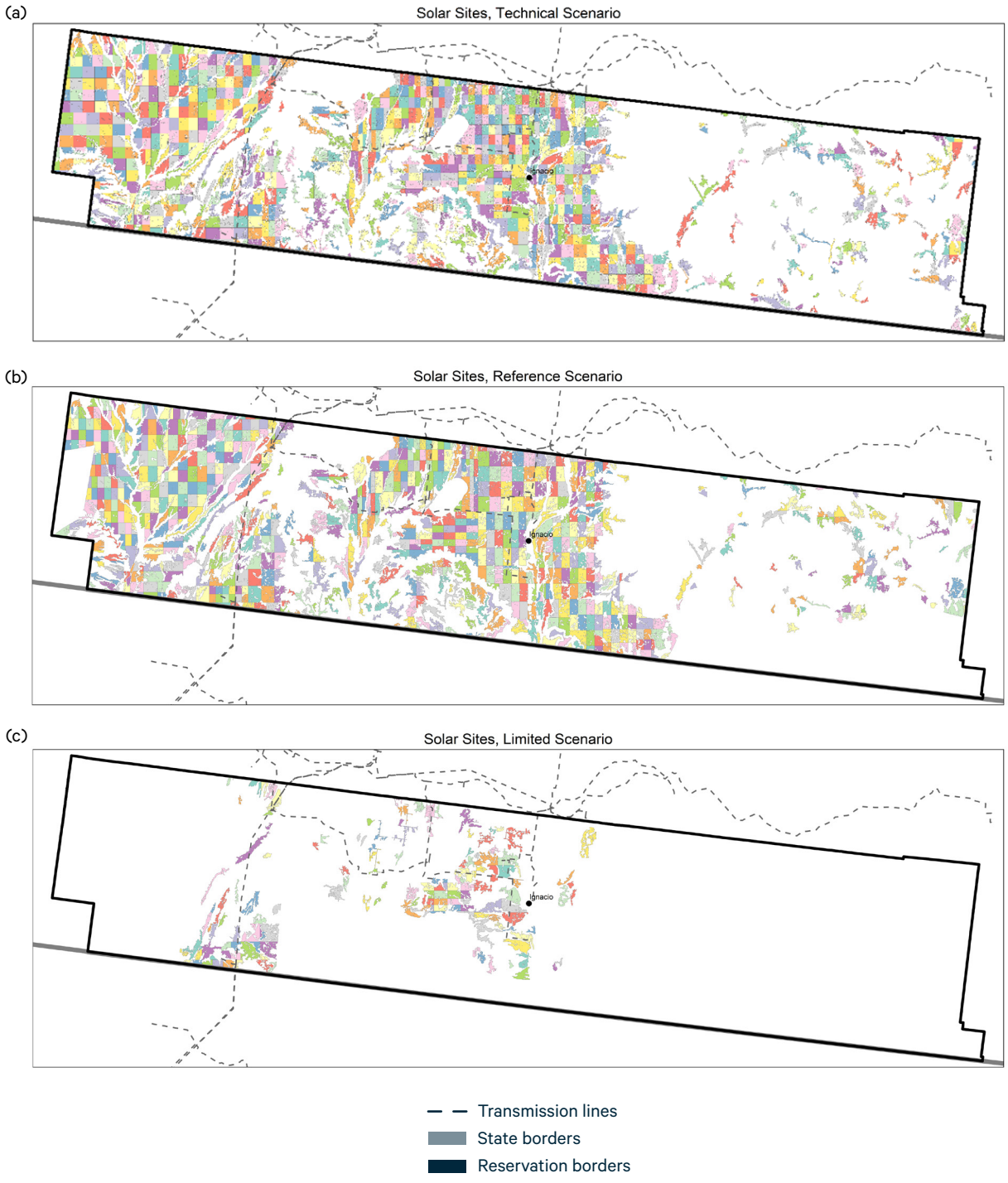
Table C.5. Site Count and Area Summary

Technology	Constraint scenario	Number of sites	Total area (km^2)
Solar	Technical	1,023	1,091
	Reference	907	995
	Limited	149	137
Wind	Technical	2,860	1,376
	Reference	2,313	1,261
	Limited	681	313

Table C.6. Site-level Statistics of Area and Distance to Transmission Line

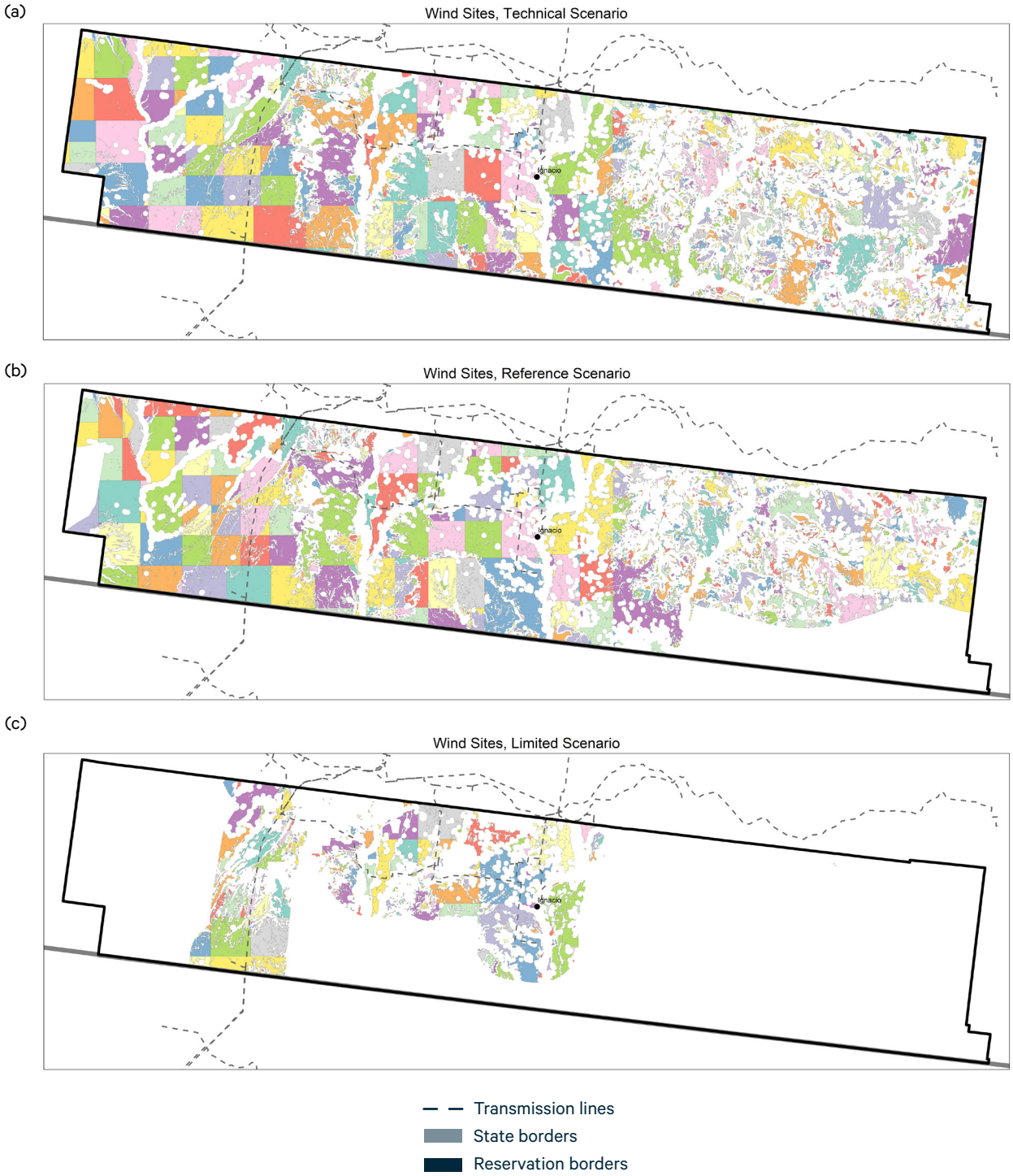
Technology	Constraint scenario	Area (km^2)			Distance to transmission line (km)		
		Minimum	Maximum	Mean	Minimum	Maximum	Mean
Solar	Technical	0.20	3.12	1.07	0	28.58	7.18
	Reference	0.20	3.09	1.10	0	19.76	6.71
	Limited	0.21	3.14	0.92	0	4.46	1.75
Wind	Technical	0.01	29.92	0.48	0	29.71	12.19
	Reference	0.01	29.45	0.55	0	19.99	9.55
	Limited	0.01	20.16	0.46	0	4.99	2.11

Figure C.2. Potential Solar Development Sites



Note: Solar sites shown for (a) technical, (b) reference, and (c) limited development scenarios. Transmission lines represented by gray dashed lines.

Figure C.3. Potential Wind Development Sites



Note: Wind sites shown for (a) technical, (b) reference, and (c) limited development scenarios. Transmission lines represented by gray dashed lines.

C.2.3. Site Surface Rights Ownership

Land within the Reservation boundaries has three broad surface rights holders: Tribal, private, and federal. Tribal land is either owned directly by the Tribe, having been purchased on the open market, or held in trust by the federal government for the benefit of the Tribe. Individual Tribal members can also hold land surface rights directly through the allotment process, which is classified as private ownership. We use geospatial data to examine the surface rights ownership of potential solar and wind sites (G. Stahnke, pers. comm., September 27, 2023). Note that we do not present maps in this section because of the confidential nature of the landownership data.

The area and percentage of each ownership category within the Reservation boundaries are presented in Table C7. Tribal lands held in trust and private (nonallotment) land surface rights each make up a little less than half of total area and combined account for about 90 percent of land area. Most of the remaining land is federally owned, primarily as part of San Juan National Forest, which encompasses Chimney Rock National Monument. Only about 2 percent of land area is under Tribal surface ownership through land purchase or private allotments to Tribal members.

Table C.7. Southern Ute Indian Tribe Surface Rights Ownership

Surface rights ownership	Area (km^2)	Percentage of total area
Tribal (trust)	1,242	45.1
Private (other)	1,212	44.0
Federal	248	9.0
Tribal (purchase)	37	1.3
Private (allotments)	17	0.6

Sources: Data from G. Stahnke (pers. comm., September 27, 2023); Esri (2018).

Here we summarize and compare the distribution of the three broad landownership categories within potential wind and solar sites and development scenarios: Tribal, private, and federal. A breakdown of more detailed surface rights categories by technology and development scenario is in Table C8.

Table C.8. Potential Site Area by Surface Rights Owner

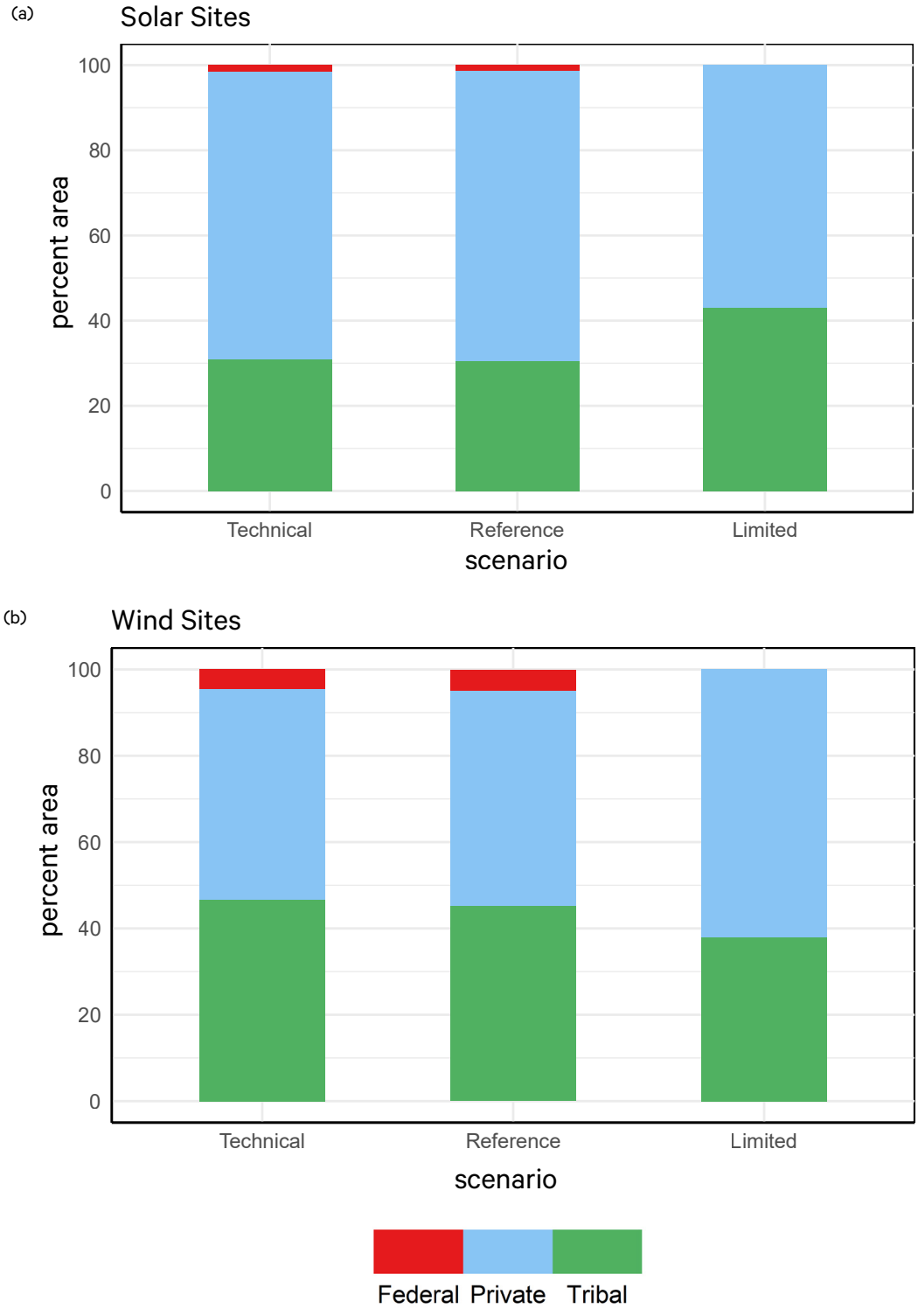
Technology	Scenario	Tribal (trust)	Tribal (purchase)	Private (other)	Private (allotments)	Federal
Solar	Technical	319.7	16.5	725.6	12.1	16.6
	Reference	296.1	8.4	668.1	10.2	12.6
	Limited	57.2	1.6	77.6	0.4	0
Wind	Technical	621.9	19.2	666.5	4.5	63.7
	Reference	560.1	9.2	623.2	4.5	63.7
	Limited	117.4	1.3	191	3.1	0

The percentage of total site area overlapping each broad surface rights category is shown in Figure C4. More private land than Tribal land is suitable for solar development under all three development scenarios. However, when operating under practical restrictions around transmission line proximity and current working lands (our limited scenario), a greater proportion of potential site surface development rights is predominantly owned by the Tribe. This pattern holds true when examining sites by their predominant surface rights holder (i.e., the landowner category that makes up the greatest proportion of site area) (Table C9).

Table C.9. Area of Potential Sites under Tribal Ownership and Number of Potential Sites under Predominantly Tribal Ownership

Technology	Scenario	Area in tribal (km^2)	Percent total scenario area, tribal	*N* sites predominantly tribal	Percent scenario sites predominantly tribal
Solar	Technical	336.2	30.8	347	33.9
	Reference	304.5	30.6	311	34.3
	Limited	58.8	43.0	54	36.2
Wind	Technical	641.1	46.6	1,813	63.4
	Reference	569.3	45.2	1,330	57.5
	Limited	118.7	38.0	354	52.0

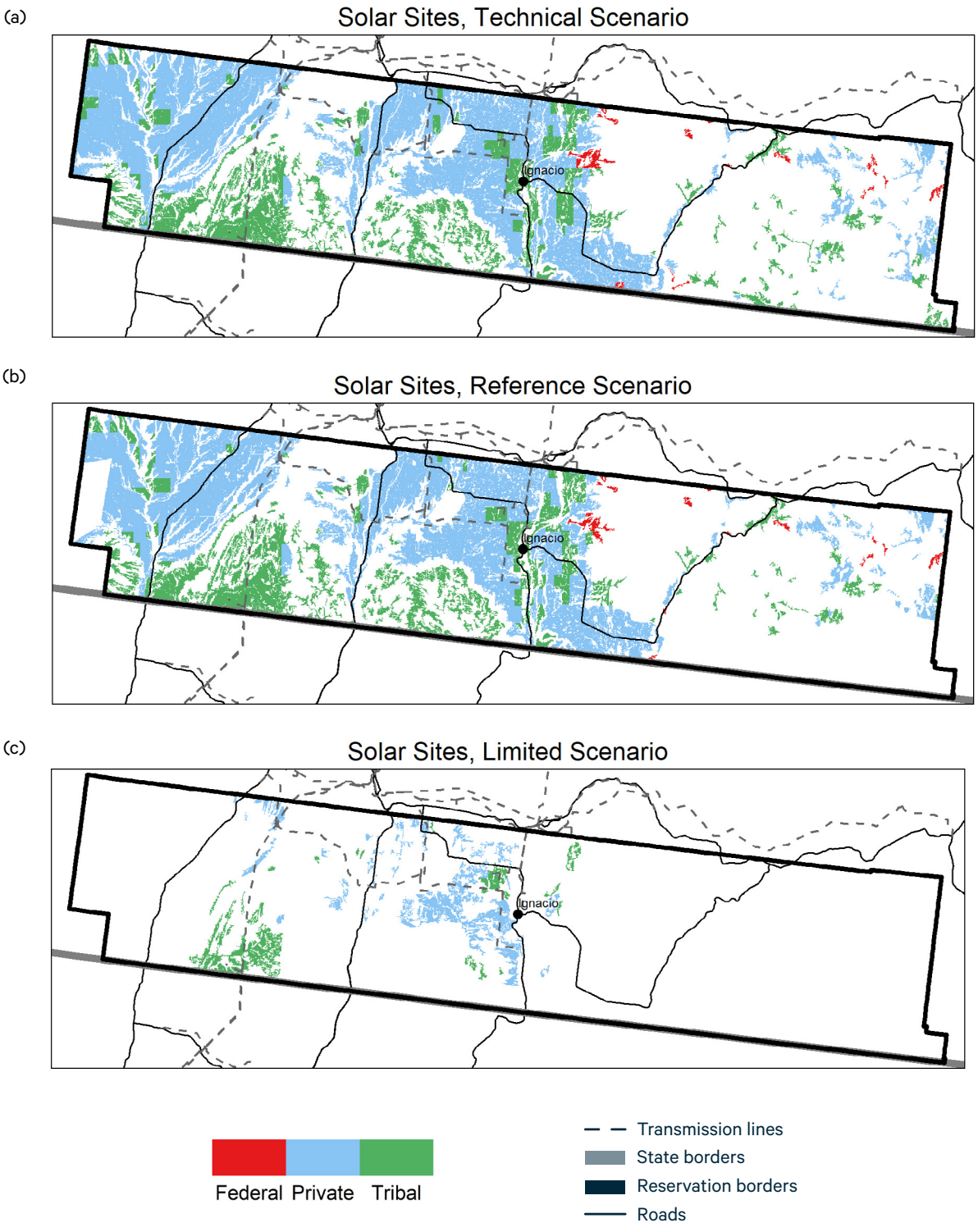
Figure C.4. Percentage of (a) Solar and (b) Wind Site Area under Tribal, Federal, and Private Surface Rights Ownership for Each Development Scenario



Most potential solar site land is subject to private landowner surface rights: about 80 percent for the technical and reference scenarios, and about 60 percent in the limited development scenarios. Solar sites in the limited development scenario occupy more Tribal land by proportion than more inclusive development scenarios, though significantly less land area overall (Figure C4 and Figure C5). Many potential solar sites that predominantly intersect private lands are omitted from limited development scenarios: those located in the Redmesa region along and west of Route 140, near the towns of Tiffany and Allison southeast of Ignacio, and along route 550 north of Bondad (Figure C5). These sites are not in the limited development scenario primarily because of the transmission line proximity condition (within 5 km), though many are also excluded because they are on prime agricultural soils or are in current use for working agriculture.

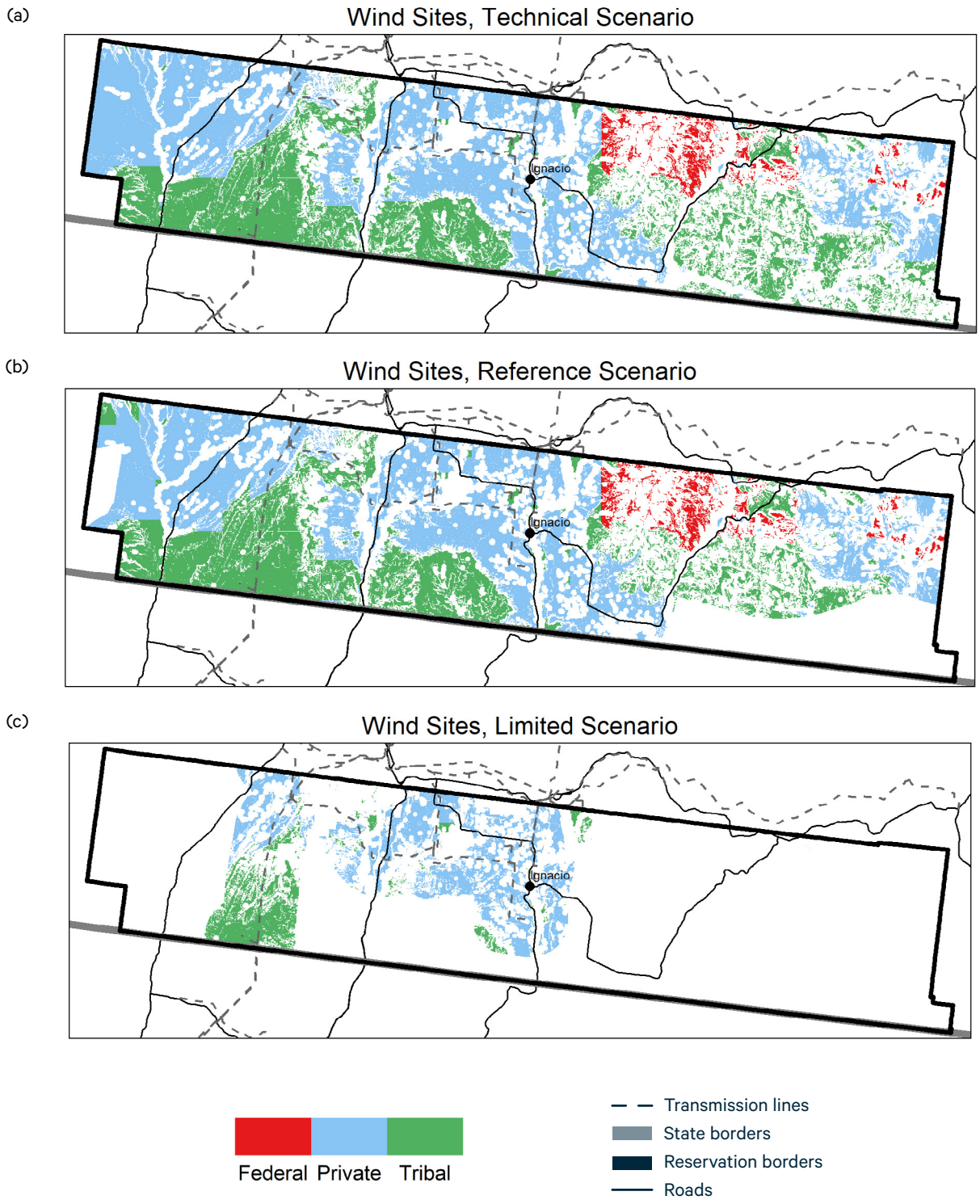
In contrast, the proportion of potential wind site land in private ownership increases from about 50 percent under technical and reference build-outs to about 60 percent under a limited build-out (Figure C4 and Figure C6). More private land remains available for wind sites within 5 km of transmission lines because the limited development scenario for wind does not prohibit development on agricultural land, and much of the private land within transmission line proximity is cultivated or in pasture. However, when looking at the number of sites by predominant ownership, more than 50 percent of sites in the limited development scenario are Tribal (Table C9).

Figure C.5. Potential Solar Development Sites by Broad Category of Surface Landownership



Note: Solar sites shown for (a) technical, (b) reference, and (c) limited development scenarios. Transmission lines represented by gray dashed lines, major roads represented by thin solid black lines.

Figure C.6. Potential Wind Development Sites by Broad Category of Surface Landownership



Note: Wind sites shown for (a) technical, (b) reference, and (c) limited development scenarios. Transmission lines represented by gray dashed lines, major roads represented by thin solid black lines.

C.2.4. Electric Capacity and Generation

Next, we examine the potential scale of electric capacity and generation at the sites described in Section C.2.2. Capacity factors are spatially linked to each site, and statistics are presented in Table C10.

Table C.10. Site Capacity Factor Statistics

Technology	Constraint scenario	Capacity factors (%)			
		Minimum	Maximum	Mean	Standard Deviation
Solar	Technical	30.7	32.9	31.7	0.4
	Reference	30.7	32.9	31.8	0.4
	Limited	31.4	32.7	31.9	0.4
	National range			20–33	
Wind	Technical	10.8	29.4	15.6	3.6
	Reference	10.8	29.4	16.0	3.8
	Limited	12.9	24.8	19.3	4.4
	National range			26–53	

Source: National capacity factor range values are from NREL (2024a).

Capacity factors for solar sites are relatively high: about 32 percent across all scenarios. Nationally, solar PV projects in the US averaged 23 percent capacity factor in 2023 (EIA 2024), indicating strong potential for solar development on the reservation. Not only does the SUIT area have a comparative advantage in terms of global horizontal irradiance, but the overall rate of resource availability does not change under the more limited development scenario.

In contrast, wind sites have relatively low capacity factors. The mean capacity factors for technical and reference build-out scenario sites are both about 16 percent, half of the mean capacity factors of solar build-outs. Nationally, US onshore wind capacity factors in 2023 were 33 percent (EIA 2024), suggesting that utility-scale wind development on the reservation may be unlikely. However, the mean level of resource availability in the limited scenario is several points higher, indicating that restricting projects to only these areas would not eliminate the best available wind resources.

These location-specific capacity factors are a major component in determining a site's potential to generate electricity, along with power density. Table C11 reports the capacity and generation potential for wind and solar across the three scenarios, and Table C12 reports site-level capacity statistics. Under all scenarios, solar offers far more promise than wind. However, solar also comes with greater land use trade-offs than wind projects because it may significantly reduce or prevent other land uses such as agriculture. Figure C7 and Figure C8 illustrate the distribution of sites under the three scenarios and show the potential electricity generation that could occur at each site.

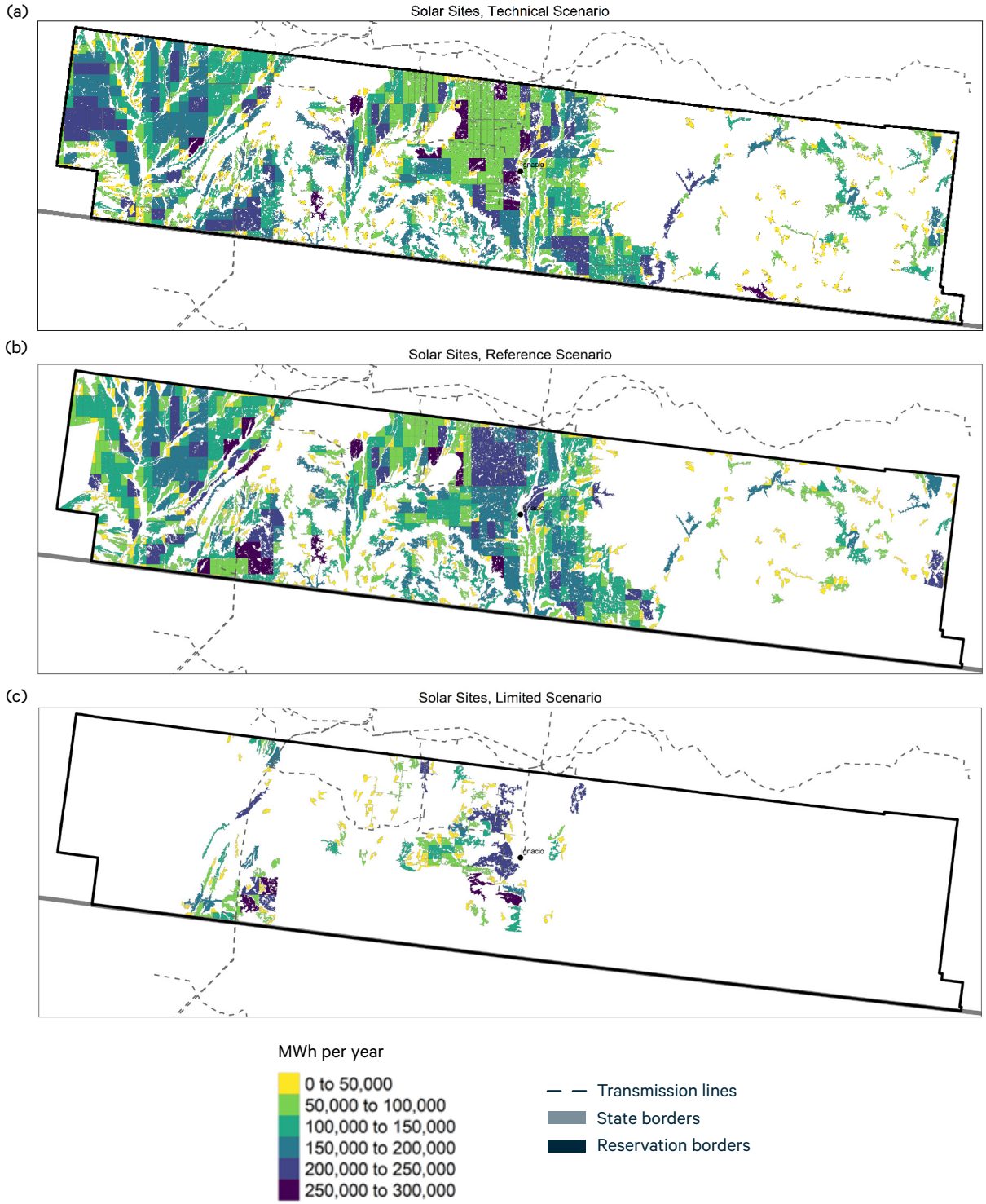
Table C.11. Site Summary of Technical Potential Capacity and Generation

Technology	Constraint scenario	Total technical potential capacity (MW)	Total technical potential generation (MWh/year)
Solar	Technical	34,898	97,090,865
	Reference	31,854	88,657,346
	Limited	4,376	12,209,275
Wind	Technical	4,127	6,969,547
	Reference	3,782	6,422,950
	Limited	938	1,524,858

Table C.12. Site-level Statistics of Technical Potential Capacity

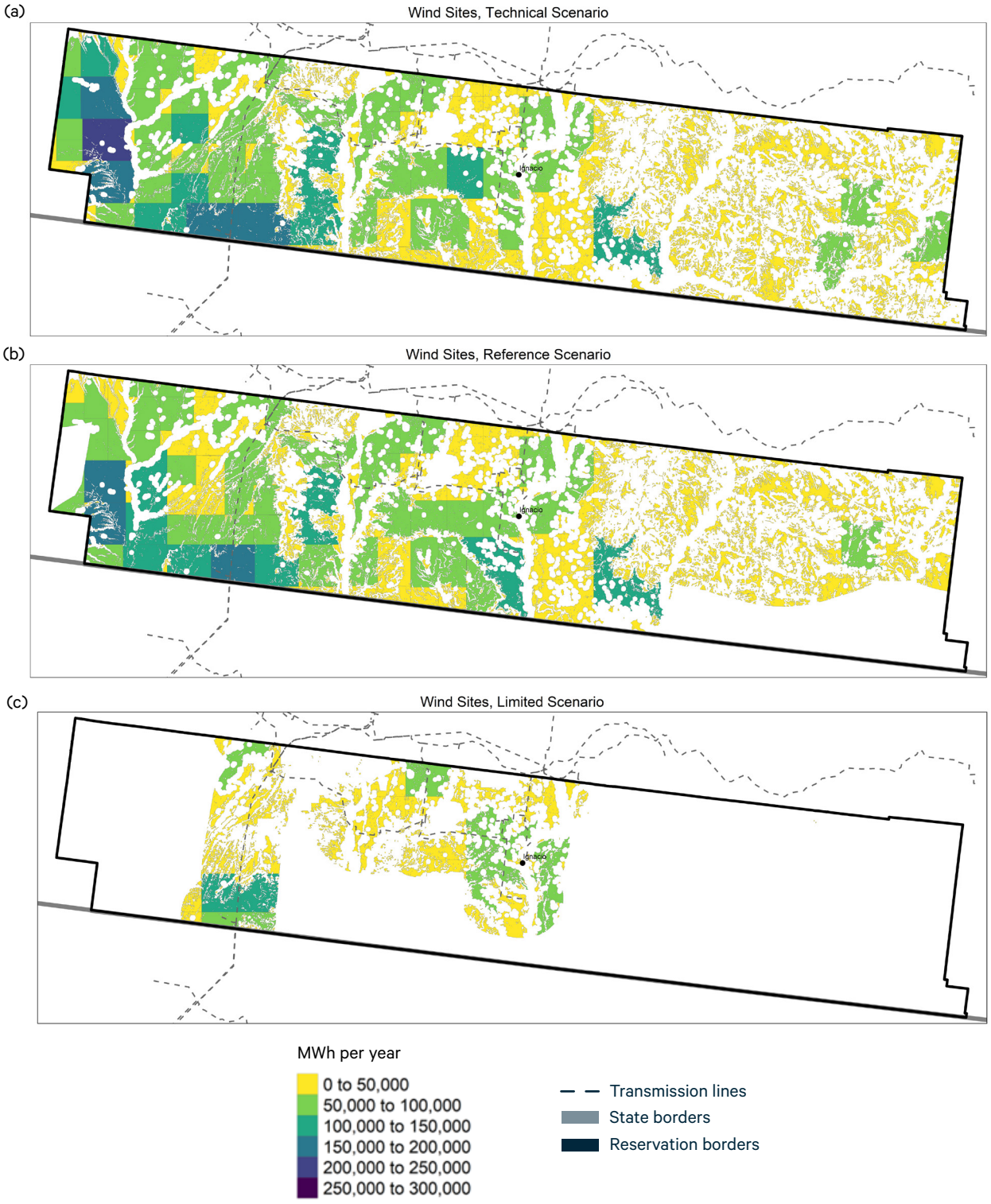
Technology	Constraint scenario	Technical potential capacity (MW)		
		Minimum	Maximum	Mean
Solar	Technical	6.41	99.73	34.11
	Reference	6.41	98.82	35.12
	Limited	6.56	100.48	29.37
Wind	Technical	0.02	89.75	1.44
	Reference	0.02	88.34	1.64
	Limited	0.02	60.49	1.38

Figure C.7. Technical Potential Capacity of Modeled Solar Development Sites



Note: Solar sites shown for (a) technical, (b) reference, and (c) limited development scenarios. Transmission lines represented by gray dashed lines.

Figure C.8. Technical Potential Capacity of Modeled Wind Development Sites



Note: Wind sites shown for (a) technical, (b) reference, and (c) limited development scenarios. Transmission lines represented by gray dashed lines.

C.2.5. Levelized Cost of Electricity

In this section, we compare site-level LCOE for solar and wind. Site-level statistics are presented in Table C13, Figure C9, and Figure C10. Site-level values are also mapped in Figure C11 and Figure C12. Variation in the LCOE stems from resource availability at a given site (capacity factor and resource class). Therefore, variation in the LCOE is similar to variation in capacity factor. Specifically, we observe a decrease in project costs associated with wind sites in the limited scenario compared with the technical and reference scenarios because harvestable wind resources are greater in locations nearer to transmission lines.

Table C.13. Site-level Statistics of Technical Potential Capacity

Technology	Constraint scenario	Levelized Cost of Energy (US$/MWh)			
		Minimum	Maximum	Mean	Standard Deviation
Solar	Technical	39.5	42.1	41.0	0.5
	Reference	39.5	42.1	40.9	0.5
	Limited	39.7	41.4	40.8	0.5
	National average*			40.0	
Wind	Technical	59.7	189.1	136.5	24.4
	Reference	59.7	189.1	133.7	25.6
	Limited	82.1	157.6	111.2	25.3
	National average*			41.9	

*National values are capacity-weighted unsubsidized averages for new resources entering service in 2027, updated to 2023$ dollars (EIA 2023; BEA 2024).

Figure C.9. Box Plot of Levelized Cost of Energy for Solar Sites

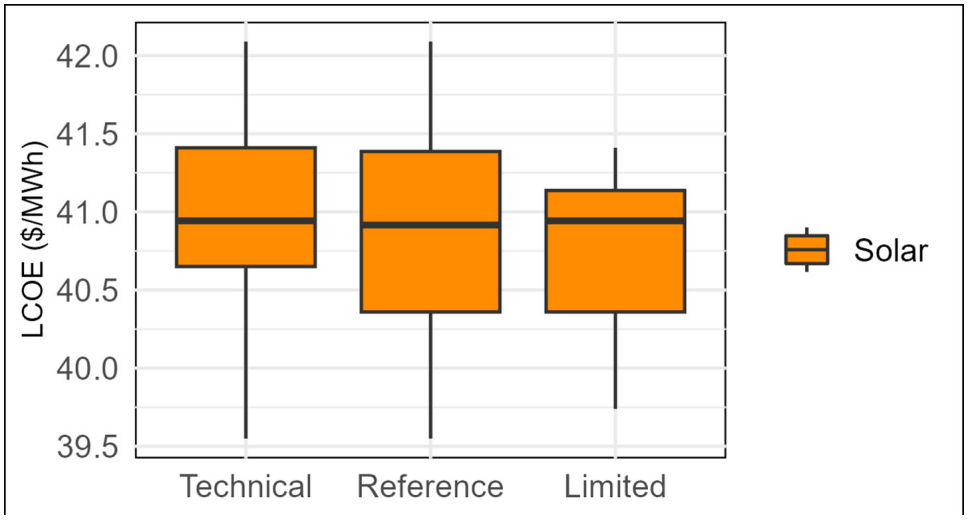


Figure C.10. Box Plot of Levelized Cost of Energy for Wind Sites

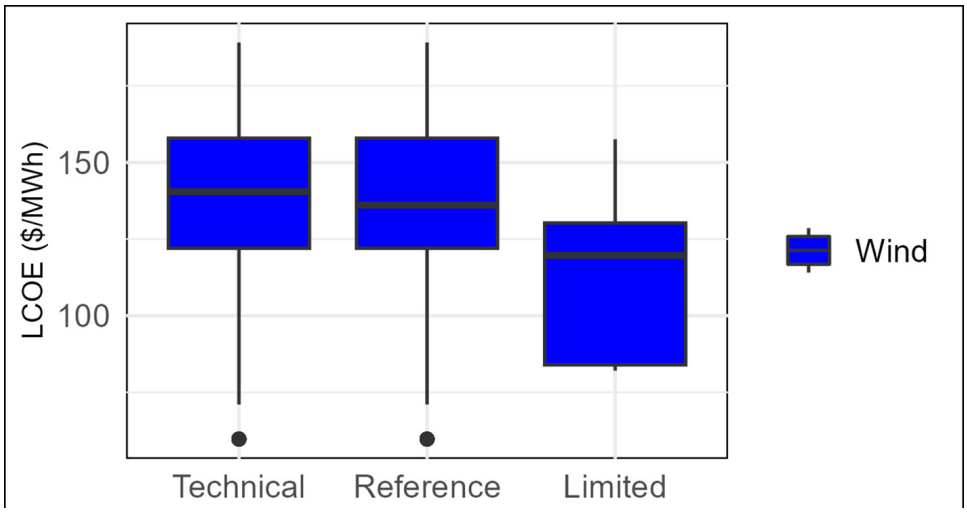


Figure C.11. Levelized Cost of Energy (US$/MWh) of Modeled Solar Development Sites

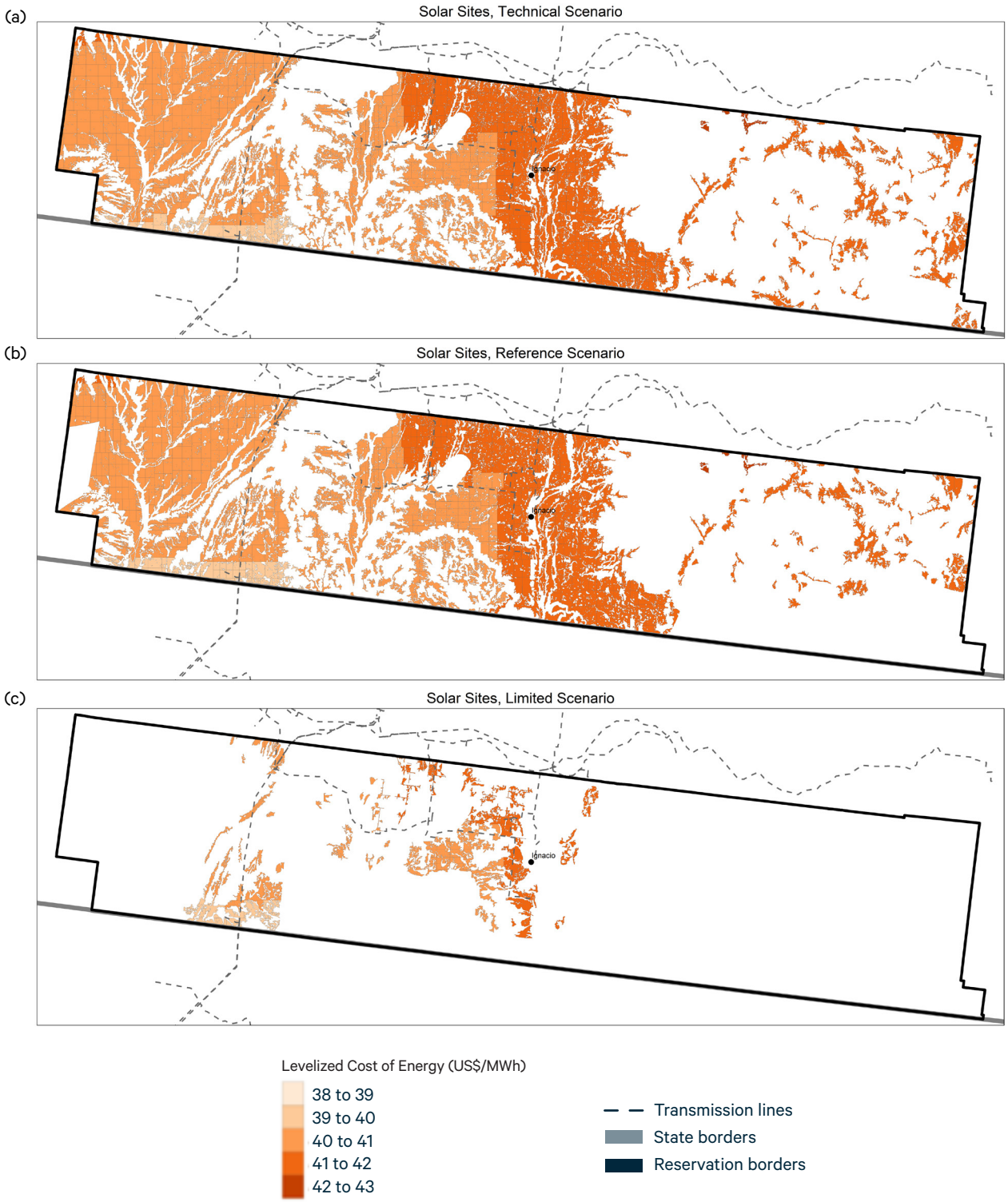
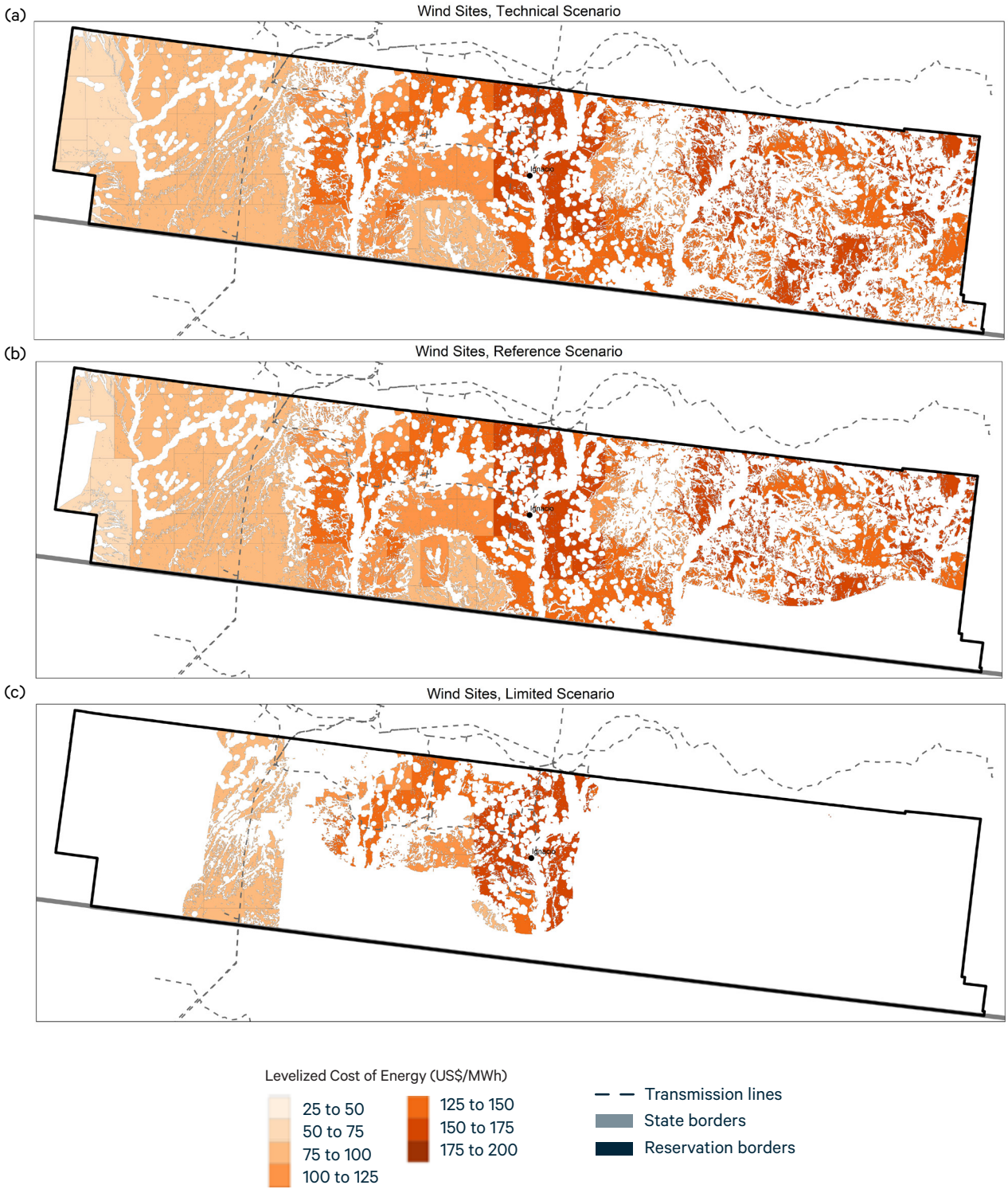


Figure C.12. Levelized Cost of Energy (US$/MWh) of Modeled Wind Development Sites



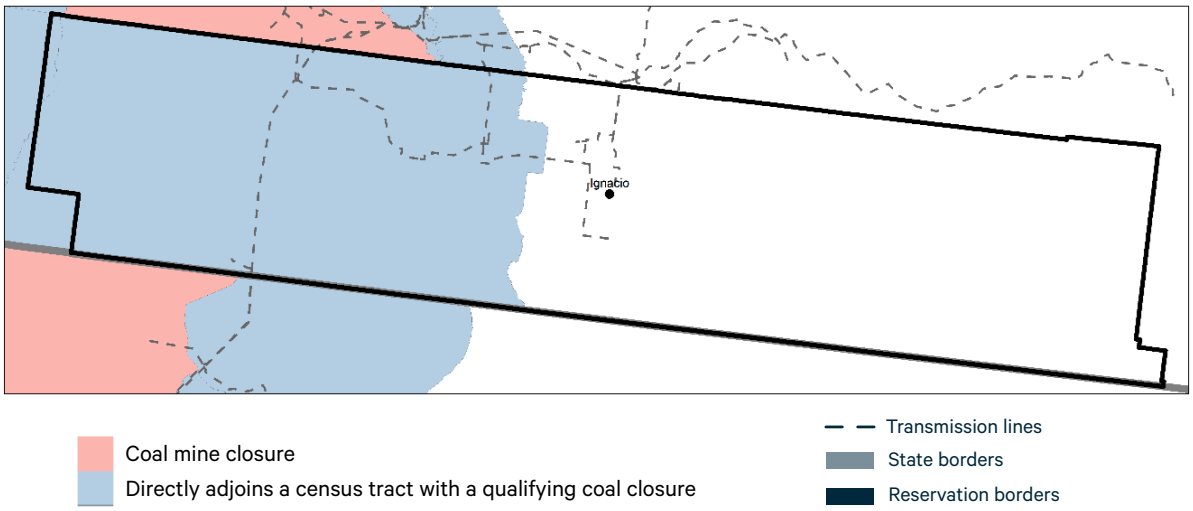
C.2.5.1. Production Tax Credit Subsidies

The Inflation Reduction Act of 2022 (IRA) included provisions to extend and bolster existing renewable energy tax incentives that were set to devalue or expire (Sherlock 2020; EPA 2022). Both tax credits effectively reduce the LCOE of a project, making it more competitive and attractive to developers. The investment tax credit (ITC) provides a percentage-based tax credit on the up-front capital cost of a project, incentivizing development. The production tax credit (PTC) provides ongoing tax credits per unit of energy produced by a facility, incentivizing production and long-term efficiency. Besides restoring the value of these credits to their full statutory amounts, the IRA added percentage-based credits for using materials produced in the United States (domestic content bonus), facilities in energy communities, and facilities in low-income communities.

Developers may choose only one type of tax credit per system. Because of its potential to provide greater benefits over the long term, especially for facilities in areas with high capacity factors, regulated utilities and project sponsors are likely to prefer the PTC, and it will probably be a major driving force in the expansion of renewable energy in the coming years (Bartlett 2023). We incorporate the PTC into the calculation of the LCOE to evaluate and compare its impact across technologies, sites, and build-out scenarios.

As of this writing, the PTC for both land-based wind and utility-scale PV technology is $27.50/MWh (assuming labor requirements are met). In addition to this base credit, projects may be eligible for two bonuses under the PTC, which provide 10 percent increases in the value of the PTC ($2.75/MWh) (DOE 2024). They include the domestic content and energy community bonuses. (A third, the low-income community bonus, is applicable only to the investment tax credit.) Projects are eligible for the domestic content bonus if they meet minimum requirements for US-produced material used for construction and components. Projects located within energy communities, as defined by the IRA and the Treasury Department, are also eligible for 10 percent increases to the base PTC value. Communities that are brownfield sites, meet unemployment rate thresholds, experienced recent coal mine closures, or are adjacent to communities experiencing recent coal mine closures are eligible (DOE 2024). The western portion of the Reservation is an energy community because it is adjacent to census tracts with qualifying coal closures (Figure C13).

Figure C.13. Map of Inflation Reduction Act Energy Communities



Source: DOE, NETL, IWG, and DOT (2023).

We calculate adjusted subsidized LCOE for each site with three potential PTC values: (1) the base PTC value, (2) the base plus the energy community bonus (affecting only sites intersecting with the energy community census tract), and (3) the base plus both the energy community bonus and the domestic content bonus (Table C14).

Table C.14. Production Tax Credit Values

	US$/MWh
Base credit	27.5
Base credit plus energy community or domestic content bonus	30.25
Base credit plus both energy community and domestic content bonuses	33

Mean site LCOE values across scenarios and PTC values are shown in Table C15, with distributions presented in Figure C14 for solar and Figure C15 for wind. Additional statistics are presented in Table C16. The base PTC subsidy, with no bonuses, decreases the mean LCOE of potential solar sites by about 75 percent. The energy community subsidy decreases the mean LCOE from the unsubsidized amount by 83–85 percent, although many LCOE values are unchanged because it affects only potential sites colocated with the energy community (Figure C14). Savings are greater in the limited scenario because, in comparison with the other build-out scenarios, a greater proportion of solar sites exists within the energy community census tract. Incorporating both bonuses cuts the mean LCOE value by about half.

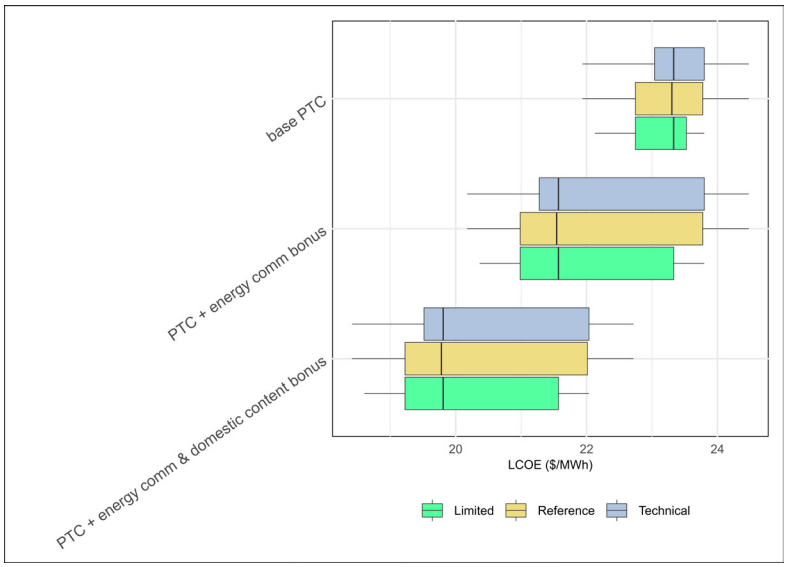
Table C.15. Site Summary of Average Levelized Cost of Energy Without and With Production Tax Credits

Technology	Constraint scenario	No Production Tax Credit	Base Production Tax Credit	Base Production Tax Credit, plus energy community bonus	Base Production Tax Credit, plus both energy community and domestic content bonuses
		Mean Value			
Solar	Technical	41.0	23.4	22.4	20.6
	Reference	40.9	23.3	22.2	20.5
	Limited	40.8	23.2	22.0	20.2
	National average	40.0[a]			19.6[b]
Wind	Technical	136.5	117.9	117.5	115.6
	Reference	133.7	115.1	114.6	112.7
	Limited	111.2	92.6	91.2	89.3
	National average	41.9[a]			20.9[b]

[a]National values are capacity-weighted unsubsidized averages for new resources entering service in 2027, updated to 2023$ dollars (EIA 2023; BEA 2024).

[b]Subsidized national values are capacity weighted federally subsidized averages for new resources entering service in 2028. Updated to 2023$ (BEA 2024; EIA 2023)

Figure C.14. Box Plot of Levelized Cost of Energy (LCOE) (US$/MWh) of Modeled Solar Development Sites with Base Production Tax Credit (PTC), Energy Community Bonus, and Both Energy Community and Domestic Content Bonuses



For wind sites, the base PTC subsidy reduces the mean LCOE value by 16–20 percent (Table C15). Proportional savings are greater in the limited scenario because the mean LCOE is lower as a result of the higher capacity factors of sites near transmission lines. With the energy community bonus, the mean LCOE value decreases by 16–22 percent, and with both bonuses, by 18–25 percent (Figure C15). Subsidy impacts on wind sites are modest compared with those on solar sites, as wind projects in this area have greater energy costs largely due to low capacity factors.

Figure C.15. Box Plot of Levelized Cost of Energy (LCOE) (US$/MWh) of Modeled Wind Development Sites with Base Production Tax Credit (PTC), Energy Community Bonus, and Both Energy Community and Domestic Content Bonuses

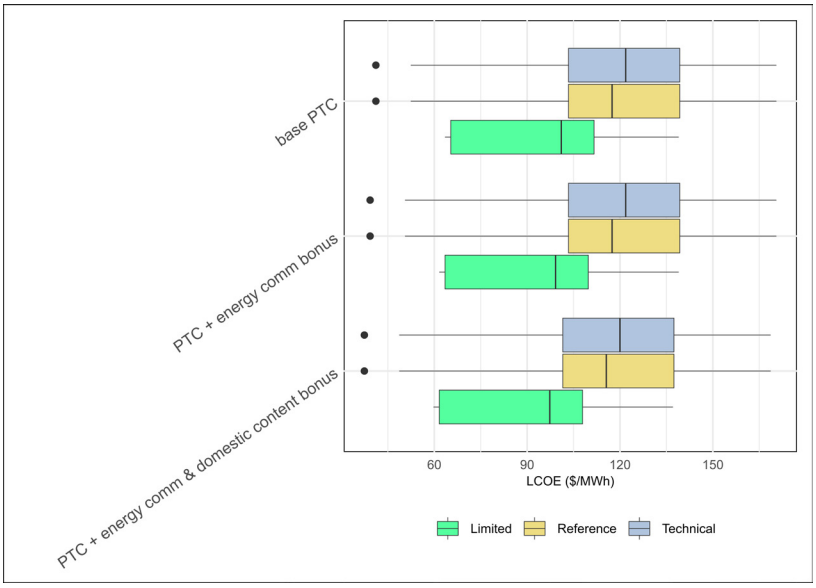


Table C.16. Levelized Cost of Energy Statistics

		Base Production Tax Credit				Base Production Tax Credit, plus energy community bonus				Base Production Tax Credit, plus both energy community and domestic content bonuses			
Technology	**Constraint Scenario**	Minimum	Maximum	Mean	Standard Deviation	Minimum	Maximum	Mean	Standard Deviation	Minimum	Maximum	Mean	Standard Deviation
Solar	Technical	21.9	24.5	23.4	0.5	20.2	24.5	22.4	1.4	18.4	22.7	20.6	1.4
	Reference	21.9	24.5	23.3	0.5	20.2	24.5	22.2	1.3	18.4	22.7	20.5	1.3
	Limited	22.1	23.8	23.2	0.5	20.4	23.8	22.0	1.1	18.6	22.0	20.2	1.1
Wind	Technical	41.1	170.5	117.9	24.4	39.3	170.5	117.5	25.0	37.4	168.7	115.6	25.0
	Reference	41.1	170.5	115.1	25.6	39.3	170.5	114.6	26.2	37.4	168.7	112.7	26.2
	Limited	63.4	139.0	92.6	25.3	61.6	139.0	91.2	25.8	59.7	137.1	89.3	25.8

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