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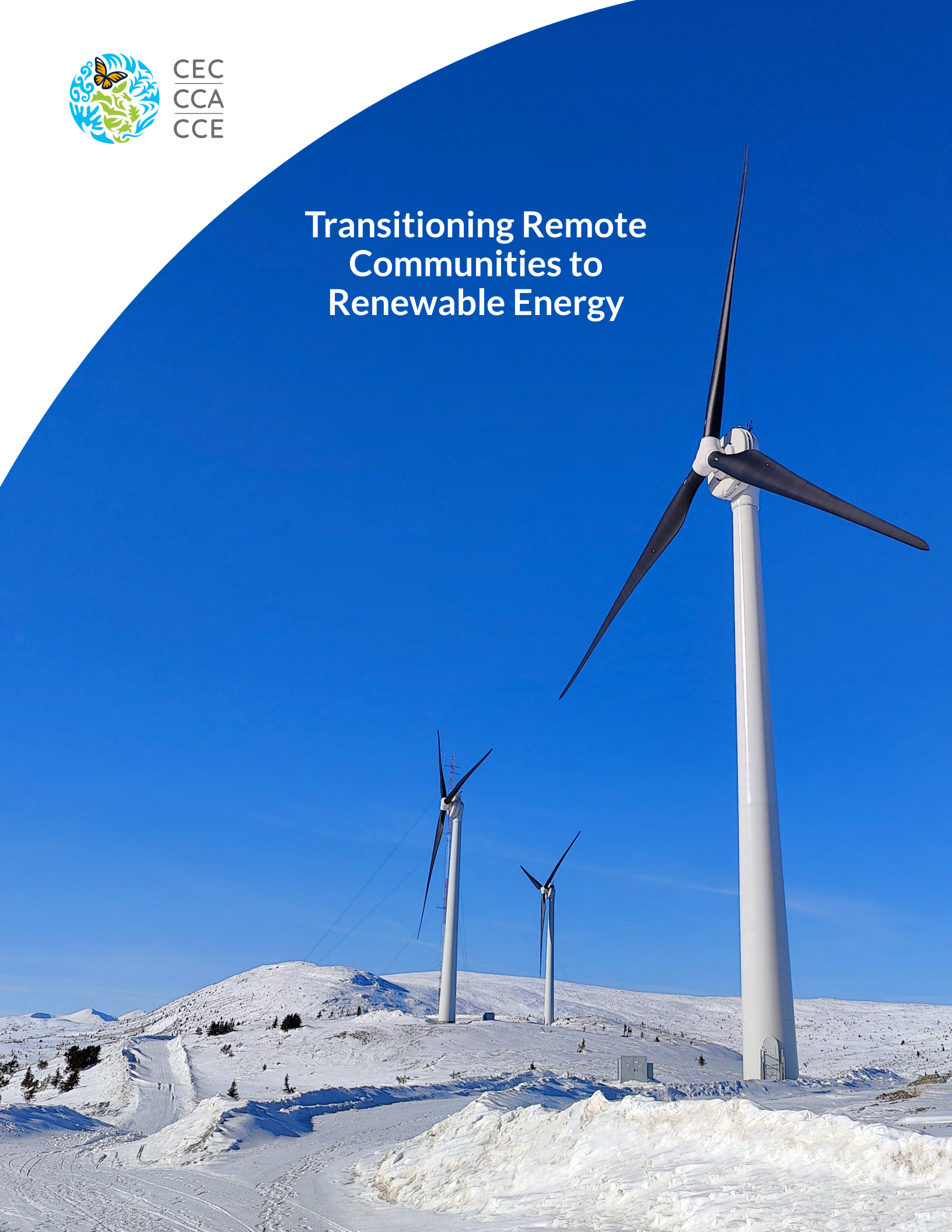
Transitioning Remote Communities to Renewable Energy



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List of Abbreviations and Acronyms

AVEC	Alaska Village Electric Cooperative
BESS	Battery Energy Storage System
BNA	Bingwi Neyaashi Anishinaabek
CEC	Commission for Environmental Cooperation
CFE	*Comisión Federal de Electricidad* (Federal Electricity Commission)
CNLP	Chu Níikwän Limited Partnership
CO_2e	Carbon Dioxide Equivalent
DOE	US Department of Energy
DTK	Dare to Know, LLC
FCPR	*Fundación Comunitaria de Puerto Rico* (Community Foundation of Puerto Rico)
FSUE	*Fondo de Servicio Universal Eléctrico* (Universal Electric Service Fund)
IPP	Independent Power Producer
IRENA	International Renewable Energy Agency
KDFN	Kwanlin Dün First Nation
KEQC	Kativik Environmental Quality Commission

kW	Kilowatt
kWh	Kilowatt-Hour
MW	Megawatt
NAB	Northwest Arctic Borough
O&M	Operations and Maintenance
PCE	Power Cost Equalization (Program)
PV	Photovoltaics
SDG&E	San Diego Gas & Electric
SENER	*Secretaría de Energía* (Ministry of Energy of Mexico)
USDA	US Department of Agriculture
W	Watt

Abstract

Remote and Indigenous communities across North America face unique challenges because of their geographic isolation, harsh climates, and limited infrastructure; they often depend on costly and environmentally damaging diesel generators for electricity. This report analyzes nine case studies from Canada, Mexico, and the United States, highlighting successful renewable energy transitions in remote communities, many of which transitions were community-led. Employing extensive interviews, site visits, and structured engagement with community members, the study focuses on self-determination, economic empowerment, environmental sustainability, and technological innovation as central themes. The diverse range of renewable energy projects includes hydroelectric systems, wind turbines, solar microgrids, and biomass heating, and demonstrates how each community leveraged local resources and cultural strengths. Key insights include the necessity of early community engagement, strategic partnerships, flexible funding mechanisms, and robust capacity-building efforts. Common challenges such as logistical complexity, financial barriers, and technological constraints were overcome through tailored approaches and strong governance structures. Numerous tables and figures throughout the report offer detailed project summaries, community insights, and critical phases of the renewable energy development. Overall, the findings provide valuable guidance for policymakers, energy practitioners, and funders aiming to support sustainable and resilient energy transitions in remote and Indigenous communities.

Executive Summary

Remote and Indigenous communities across North America face some of the continent's toughest energy and climate challenges—and they also lead in some of the most important energy solutions. This report highlights nine communities in Canada, Mexico, and the United States that are charting their own path toward energy independence through local, renewable energy systems.

- **Canada:** Innavik Hydro Project (Inukjuak, Quebec), Haeckel Hill–Thay T'äw Wind Energy Project (Whitehorse, Yukon), and Bingwi Neyaashi Anishinaabek Biomass Heating Project (Lake Nipigon, Ontario).
- **Mexico:** Solar panels in Yoloxochio (Zongolica, Veracruz), San José de Natora (Sahuaripa, Sonora), and Magdaleno Aguilar (Llera, Tamaulipas).
- **United States:** Shungnak and Kobuk solar panels and battery energy storage (Alaska), Borrego Springs solar microgrid (California), and Toro Negro solar microgrid (Puerto Rico).

The case studies included in this report are not just examples of new technology installations. They are stories of self-determination and of communities building projects that reflect their values, priorities, and long-term goals. Whether it is an Inuit-run hydropower project in northern Quebec, wind turbines owned by a First Nation government in the Yukon, or off-grid microgrids and solar panels in remote parts of Alaska and Mexico, each project demonstrates what is possible when energy development is rooted in place and led by those who live there.

These projects have reduced diesel use, cut carbon emissions, created local jobs, and—most importantly—put control of energy systems into the hands of the communities they serve. The transitions have not always been easy, but common lessons stand out: success depends on trusted partnerships, flexible funding, and technical support that grows with the project.
To help inform future efforts, the report also outlines how communities move through the different levels of energy transition—from early planning to long-term operations. The report can serve as a tool for funders, governments, and energy practitioners who want to work effectively with communities, not around them.

What these nine communities offer is more than inspiration—they offer direction. They remind us that real progress on climate and energy equity is not just about megawatts and dollars. It is about relationships, respect, and sustained investment in people and places.

Preface

Remote and Indigenous communities across North America have historically faced significant challenges caused by geographic isolation, energy insecurity, and reliance on costly fossil fuels. Recognizing the urgency of addressing these challenges, the Commission for Environmental Cooperation commissioned this report to document and analyze successful renewable energy transitions in these communities. This work was undertaken to provide valuable insights, practical lessons, and replicable models for policymakers, energy practitioners, funding agencies, and communities embarking on similar journeys toward energy independence and resilience. By highlighting diverse, renewable energy projects designed to serve community needs and priorities, this report underscores the importance of self-determination, culturally aligned strategies, and sustainable economic development. It aims to foster greater understanding of the complexities and opportunities associated with energy transitions in remote settings, ultimately supporting broader efforts toward climate resilience and equitable energy access across North America.

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This report was made possible through the collaboration and generosity of the communities, organizations, and individuals who shared their time, experiences, and insights throughout the research and interview process.

We especially acknowledge the contributions of the project's steering committee and supporting agencies, whose expertise and feedback strengthened the direction and focus of this report. This includes representatives from the following:

- Natural Resources Canada
- Crown-Indigenous Relations and Northern Affairs Canada
- Ministry of Energy, Mexico (*Secretaría de Energía*)
- Federal Electricity Commission, Mexico (*Comisión Federal de Electricidad*)
- National Institute of Ecology and Climate Change, Mexico (*Instituto Nacional de Ecología y Cambio Climático*)
- US Environmental Protection Agency

We are grateful to the community leaders, residents, and project partners in the nine case study locations, who generously shared their stories and opened their doors to our team:

- **Bingwi Neyaashi Anishinaabek (Ontario, Canada):** to the community leaders, administrative staff, Papasay Sawmill representatives, and TBT Engineering Limited for sharing their long-term vision and biomass energy leadership.
- **Inukjuak (Quebec, Canada):** to Pituvik Landholding Corporation, the Innavik Hydro project team, and Innergex Renewable Energy Inc. for their collaboration and transparency.
- **Whitehorse (Yukon, Canada):** to Northern Energy Capital, Chu Níikwän LP, Eagle Hill Energy LP, Yukon Energy Corporation, and Kwanlin Dün First Nation leaders for their insights into renewable energy governance.
- **Shungnak and Kobuk (Alaska, United States):** to local regional leaders and Ingemar Mathiasson for their commitment to energy resilience and intercommunity coordination.
- **Borrego Springs (California, United States):** to San Diego Gas & Electric and local community members for their reflections on microgrid implementation and community impact.
- **Toro Negro (Puerto Rico, United States):** to community leaders, Comunidad Toro Negro, Fundación Comunitaria de Puerto Rico, and Somos Solar for modeling energy sovereignty in action.

- **Yoloxochio (Veracruz, Mexico):** to local leaders and residents for their perseverance and openness in navigating the challenges of off-grid solar systems.
- **San José de Natora (Sonora, Mexico):** to community members, educators, and local authorities for sharing their experiences with energy access and system maintenance.
- **Magdaleno Aguilar (Tamaulipas, Mexico):** to residents for their engagement and reflections on rural solar electrification.

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We also recognize the contributions of research collaborators at Dare to Know, LLC, as well as the support of partners from the Global Initiative on Transitioning Remote Communities to Renewable Energy, promoted by the International Renewable Energy Agency (IRENA).

This report is offered in a spirit of respect and reciprocity. Any errors or omissions are the responsibility of the authors, and we welcome continued dialogue with all participating communities.

1. Introduction

The Transitioning Remote Communities to Renewable Energy initiative documents strategies for transitioning remote North American communities to cleaner and more reliable sources of energy. In collaboration with the Commission for Environmental Cooperation (CEC) and the International Renewable Energy Agency, and with strategic guidance from technical and policy representatives from Canada, Mexico and the United States, the Dare to Know, LLC (DTK) project team consulted with nine remote communities in the North American region that implemented renewable energy projects (Table 1). This report describes those projects and summarizes the lessons learned by the communities throughout project implementation. The following map presents the locations of the case study communities.

Table 1. Location of selected communities, by country

Canada	United States	Mexico
Bingwi Neyaashi Anishinaabek (Ontario)	Borrego Springs (California)	Magdaleno Aguilar (Tamaulipas)
Inukjuak (Quebec)	Shungnak and Kobuk (Alaska)	San José de Natora (Sonora)
Whitehorse (Yukon)	Toro Negro (Puerto Rico)	Yoloxochio (Veracruz)

Energy generation in remote communities is challenged by geography, climate, and available infrastructure. Isolation, rugged terrain, extreme weather, and other factors make the development and maintenance of energy generation systems difficult and expensive.

Transporting materials and equipment to these communities often requires specialized logistics, including air transport, ice roads, or barges, which add considerable cost and complexity to energy projects. Because many remote communities lack access to the main electrical grid, they rely on costly and environmentally damaging diesel generators. In this report, remote communities are defined as those that experience geographic, infrastructural, or functional isolation—such as in energy, transportation, or communication—from centralized systems, resulting in persistent challenges to service reliability, affordability, or access.

Socioeconomic factors add another layer of complexity. Remote communities often have small populations, which can limit the economic feasibility of large-scale energy projects. High up-front costs and long payback periods can deter investors. Moreover, small communities may not have the technical expertise and available workforce to install, operate, and maintain advanced energy systems, and therefore need ongoing external support and training.

Despite these challenges, there are opportunities for innovation and collaboration. The key findings from the nine case study projects discussed in this report reveal common themes across community energy projects, including local participation in project development; environmental sustainability; economic empowerment; technological innovation; and cultural significance. Each project demonstrates how communities can overcome the challenges inherent to energy generation in remote locations by leveraging local resources, fostering community involvement, and implementing solutions tailored to their specific needs and conditions. These nine projects are examples of how remote communities can realize sustainable and resilient energy generation.

The next sections provide energy project summaries and key findings for the case study communities, presented in north-to-south geographical order: Canada, the United States, and Mexico. Section 5 discusses the common themes found across the case study projects.

2. Canadian Case Studies

Overview

There are more than 200 remote communities across Canada, of which more than three-quarters are Indigenous. Most of these communities are not connected to the North American electricity grid and use fossil fuels such as diesel for heat and power. A reliable energy supply is essential for the safety of these communities because of their remoteness and cold climates. But the remote locations and extreme conditions present logistical challenges for safe and reliable fuel transportation, often requiring seasonal ice roads, barges, and air tankers.

Although diesel is a reliable source of energy, there are disadvantages to its use, beyond the logistical challenges of delivery to remote locations. Diesel use negatively impacts the environment through greenhouse gas emissions and local air pollution and carries the risk of causing contamination from potential fuel spills during transportation, storage, and operation. Fluctuations in the market price of diesel, and expensive transportation to remote areas result in high costs to communities, governments, and ratepayers to operate and maintain diesel generating systems.

Energy needs vary in remote communities in Canada, depending on community priorities and financial, technical, and organizational capacities. In most cases, communities operate on their own microgrids. Large-scale energy generation projects are often not economical because of high up-front costs and the logistical challenges of building infrastructure in remote locations. In the northern territories of Nunavut, Yukon, and the Northwest Territories, a very small base of ratepayers and taxpayers supports the operation and maintenance of energy systems, which complicates the economics of pursuing large projects.

The integration of renewable energy systems into existing diesel-powered microgrids is challenged by extreme climatic conditions, such as heavy snowfall and ice accumulation, and by prolonged periods of darkness. These conditions can increase the variability of power supply from renewable technologies driven by wind, water, and the sun, and compromise the safety and reliability of a community's energy supply. Integrating renewable energy technologies requires careful planning and adaptation to local conditions to ensure the sustainability, safety, and reliability of remote energy systems.

In response to Canada's goals to achieve a net-zero economy by 2050, a number of federal, provincial, and territorial programs—like the Clean Energy for Rural and Remote Communities program and the Northern Responsible Energy Approach for Community Heat and Electricity program, among others—are taking action to support remote and Indigenous communities as they transition to clean energy sources for heat and power. These efforts are guided by broader strategies such as the Arctic and Northern Policy Framework, which provide long-term direction for infrastructure resilience and Indigenous self-determination in the North. Additional details on these enabling policies and funding structures are provided in the Annex.

The information-gathering process in Canada focused on three remote communities in the Yukon territory and the provinces of Ontario and Quebec that are engaged in efforts to transition to renewable energy. The goal of the interviews was to understand the economic, environmental, and social impact of the communities' renewable energy initiatives, key challenges related to the initiatives, and the role of local governance in project implementation.

Rooted in Vision, Driven by Community: Bingwi Neyaashi Anishinaabek's Strategic Energy Transition

> "We've built this with a small team and a strong vision. Other First Nations can do it too—but it takes persistence and a commitment to community engagement."
>
> Chief Paul Gladu, Bingwi Neyaashi Anishinaabek

Bingwi Neyaashi Anishinaabek (BNA), formerly known as Sand Point First Nation, is a small but resilient community located on the southeastern shore of Lake Nipigon in Ontario. Home to approximately 250 members, BNA maintains a strong connection to the surrounding boreal forest and the pristine waters of the lake—resources that remain central to the community's culture, economy, and daily life.

The community's remote location—over an hour's drive from the nearest urban center via long stretches of rural highway—has presented challenges to infrastructure development, access to services, and economic growth. At the same time, this isolation has fostered a spirit of innovation, self-reliance, and deep-rooted connection to place.

For decades, BNA faced the consequences of colonial policies that removed members from their traditional territory, leaving the nation without a land base or legal recognition. This dislocation disrupted governance, cultural continuity, and economic development. In recent years, however, BNA has made remarkable progress in reclaiming its land and rebuilding its local economy.

A central part of this revitalization is the Papasay Sawmill—currently the only business operating in Sand Point. The sawmill processes local timber and creates year-round employment opportunities for community members. It also supplies fuel for BNA's new biomass heating system, which uses sawmill residue to heat community buildings and homes. Prior to this district-wide heating system, workers endured subzero temperatures—sometimes as cold as 40°C—with only donated diesel heaters. These were not only inadequate but also heavily polluting.

The new biomass system has greatly improved working conditions and energy resilience. Although BNA is connected to the electrical grid via the A4L line, this long radial transmission line is unreliable and frequently experiences extended blackouts, which poses serious risks in winter, when homes rely on electric baseboard heating. The biomass system provides a safer, more sustainable alternative for heating and supports BNA's broader goals of energy security and self-sufficiency.

In tandem with its renewable energy initiatives, BNA has expanded its built environment in recent years. The community now includes 25 residential homes, a community center, and other essential facilities—all part of a broader vision for sustainable, locally driven development.

Energy Transition Project Summary

BNA's journey to renewable energy reflects a long-term vision of environmental stewardship, cultural preservation, and economic empowerment. The community has implemented the Bingwi Neyaashi Anishinaabek Sawmill Biomass-Fueled Heating System Project, a transformative initiative to replace the sawmill's diesel-based heating system with a biomass system fueled by locally sourced wood residue. This project involved installing a Froling T4 150-kilowatt (kW) biomass boiler in a shipping container. Table 2 gives a summary of the project.

Table 2. Summary of the Bingwi Neyaashi Anishinaabek Biomass Heating Project

Project Details	Description
Technology	Biomass heating system
Installed capacity	150 kW
Timeline	Planning: fall 2017–fall 2019 Construction: November 2019–March 2020
Total cost	C$1.05 million (US$734,800) (ICE Network 2020)
Funding sources	C$1.05 million from the Clean Energy for Rural and Remote Communities program
Project lead and key partners	BNA Council, Clean Energy for Rural and Remote Communities program, Natural Resources Canada, local contractors
Ownership structure	Solely owned and operated by BNA
Project impacts	• The project supported the local bioeconomy through the value-added use of sawmill residue, while avoiding the use of ~13,000 liters of diesel annually, saving an estimated C$26,000 per year (TBT Engineering Limited, personal communication, 8 January 2025). • The project reduced emissions by ~34.84 tonnes of carbon dioxide equivalent (CO_2e) per year by transitioning from diesel to biomass to heat the Papasay Sawmill. • BNA Council Members and Papasay Sawmill staff gained experience with biomass systems, laying the groundwork for scaling up to a community-wide district heating loop that is starting construction in 2025.

Table 3. Interview findings on the Bingwi Neyaashi Anishinaabek Biomass Heating System, by project development phase

Project Development Phase	Key Findings
Planning	• Community members participated in defining priorities, zoning areas for development, and aligning the renewable energy project with community goals. • BNA held four or five general meetings annually to inform and involve community members. • BNA established a governance structure to oversee the project to ensure transparency and accountability.
Technology selection and procurement	• The biomass heating system's ability to use wood chips from sawmill residue aligns with BNA's resource-based economy. • Engagement with key partners, such as Natural Resources Canada, ensured technical and financial feasibility. • The community decided on biomass technology before working with engineers to design the system.
Financing and permitting	• Non-repayable contributions were received from Natural Resources Canada, from the Clean Energy for Rural and Remote Communities Program. • No permitting was required because the project is on self-governed First Nations land.
Installation and commissioning	• The installation of the biomass system was a milestone for BNA. • The community addressed limited internal expertise with biomass systems by hiring TBT Engineering to serve as project managers and provide technical guidance throughout the project life cycle. • BNA experienced capacity constraints from managing multiple initiatives at once. This was mitigated by engaging TBT Engineering to oversee project coordination and ensure timelines were maintained. Regular meetings between BNA, TBT, and the contractor helped keep the project on track. • To manage the integration of multiple technologies, a local contractor, Biothermic, was selected through a competitive tendering process, to help ensure timely responses to technical issues and determine the local availability of replacement parts. • On-site technical support during installation (provided by Art Gladu, a millwright by trade) enabled prompt resolution of installation challenges.
Operations	• Biothermic (the installer) provided training to an operator and continues to provide remote troubleshooting.

Key Findings

BNA's renewable energy journey highlights a blend of strategic planning, collective determination, and effective collaboration. The project has fostered a sense of collective accomplishment, with many community members describing it as a milestone in BNA's journey toward reclaiming their land and resources. Key interview findings, by project development phase, are summarized in Table 3.

BNA's journey demonstrates the power of self-determination, vision, and strategic partnerships in driving community-led energy transformation. Its progress—from sawmill biomass to a community-wide district heating project—reflects a deliberate approach to growth, grounded in planning and sustainability. Specific lessons stood out during the interview process with the BNA community:

- Community vision and engagement are key. The foundation of the project's success lies in the unity of the BNA community. Through regular surveys, workshops, and open forums, the BNA Council ensured that community priorities were heard and used to shape the project's outcomes. For instance, one participant highlighted how discussions on resource allocation led to redesigning certain aspects of the system to better align with community needs, illustrating the tangible impact of these engagements. As Chief Paul Gladu shared, "We didn't just build a heating system, we built trust and a shared vision for our future."
- The availability of funding and expertise was crucial to success. A significant hurdle was the securing of reliable financing. Collaboration with organizations like Natural Resources Canada proved invaluable, not only in terms of financial support but also in accessing technical expertise. As one project lead stated, "When resources were tight, our partnerships gave us the push to keep going."
- Navigating bureaucracy to overcome funding challenges requires patience and persistence. The BNA Council's strategic advocacy ensured the project adhered to complex planning processes while staying true to the community's vision.

Looking ahead, BNA's leadership is focused on completing the design and securing full funding for the district biomass heating system, which will expand clean, locally sourced heating across the community. The following next steps are in process or planned by the community:

- The leadership is preparing to pursue financing through the First Nations Finance Authority, building on its financial management certification and strengthening its ability to support future infrastructure projects.
- Efforts are also underway to develop a robust operations and maintenance plan for the district heating system, ensuring long-term reliability.
- BNA recognizes that youth engagement is central to project success, with training opportunities in forestry, construction, and system operations preparing the next generation to carry forward BNA's energy and governance legacy.

Harnessing the River, Strengthening the People: Inukjuak's Innavik Hydro Project

> "I think it's very important for an Inuit-led project like this to start from the bottom—to have the community lead the project. I see my people standing on their own two feet and working on their own ideas."
> —President Tommy Palliser, Pituvik Landholding Corporation

Inukjuak is a remote Inuit community located along the Hudson Bay coast in the Nunavik region of northern Quebec. According to the 2021 Canadian Census, the population is 1,805, with approximately 99 percent identifying as Inuit. The community experiences a subarctic climate characterized by long, harsh winters and short, cool summers, which contribute to the challenges of infrastructure development and fuel delivery. Inukjuak is not accessible by road and relies on seasonal air and marine transport, reinforcing its logistical isolation.

The local economy is primarily based on public-sector employment, small-scale retail, and traditional harvesting activities, including fishing and hunting. Deep cultural ties to the land, language, and Inuit traditions continue to shape community life and identity. The Pituvik Landholding Corporation plays a key role in representing the community's interests and advancing local priorities, including efforts to transition to cleaner, more sustainable energy systems.

Table 4. Summary of the Innavik Hydro Project

Project Details	Description
Technology	Run-of-river hydroelectric dam
Installed capacity	7.5 MW (Innergex Renewable Energy Inc. 2020)
Timeline	2016 (initiation)–2023 (completion) (Innergex Renewable Energy Inc. n.d.)
Total cost	C$127 million (US$89 million) (Innergex Renewable Energy Inc. 2020)
Contracted energy price	C$0.19/kWh (US$0.14/kWh)* (Innavik Hydro, and Hydro-Québec Distribution 2019)
Funding sources	• Mix of project debt and equity contributions from Innergex and the Pituvik Landholding Corporation. • Project debt covered 75–85 percent of the total cost (~C$95–108 million), using non-recourse financing (Innergex Renewable Energy Inc. 2020). • Equity contributions totaled ~C$35 million, split equally: Pituvik's C$17.5 million was fully funded by government grants (approx. 60–65 percent federal, 35–40 percent provincial) (Innergex Renewable Energy Inc. 2020). • Innergex contributed C$17.5 million in private equity (Innergex Renewable Energy Inc. 2020).
Project lead and key partners	Innergex, Nunavik Regional Government, Kativik Environmental Quality Commission (KEQC), Pituvik Landholding Corporation (Innergex Renewable Energy Inc. 2020, Pituvik Landholding Corporation 2024).
Ownership structure	50/50 partnership model between Innergex and Pituvik Landholding Corporation (Innergex Renewable Energy Inc. 2020).
Project impacts	• The project reduced diesel dependence by 80 percent. Approximately 700,000 tonnes of CO□e emissions are avoided over the project's 40-year lifespan (Innergex Renewable Energy Inc. n.d.). • Downstream fish habitats are improved through regulated water flow (Pituvik Landholding Corporation 2024). • The project created local jobs and built capacity for project construction and operation (Innergex Renewable Energy Inc. n.d.). • Projected annual revenues of C$8.6 million will support community-driven initiatives (Innavik Hydro 2020).

* The C$0.19/kWh figure was derived by dividing the total contracted energy cost by the expected delivered energy over the agreement term. While actual values may vary, this provides a reasonable estimate of the effective power purchase agreement (PPA) rate.

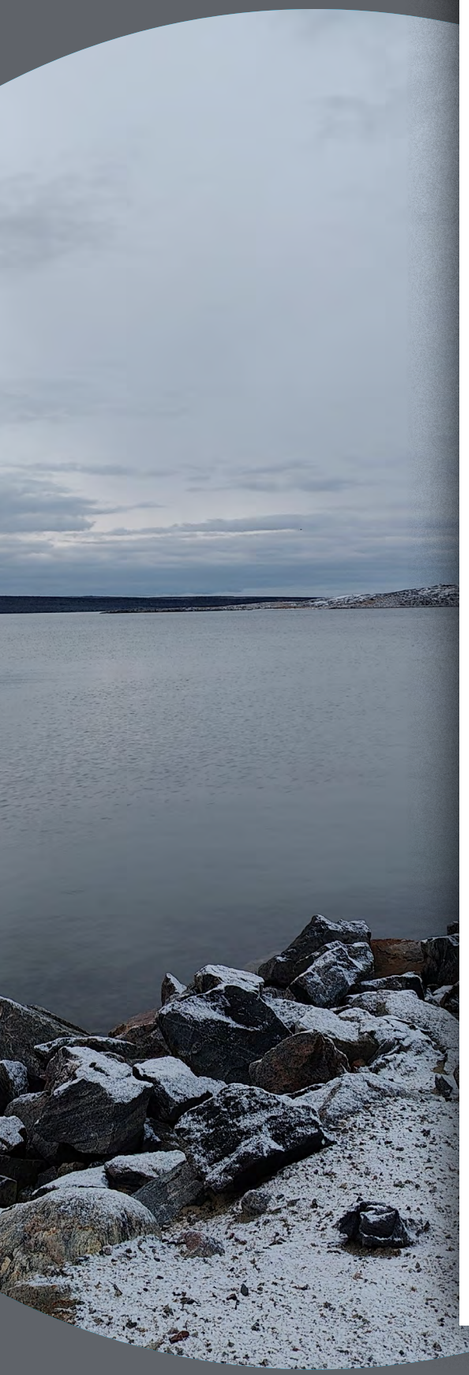


Table 5. Interview findings on the Innavik Hydro Project, by project development phase

Project Development Phase	Key Findings
Planning	• Community engagement emphasized local decision-making and input. Pituvik leaders prioritized using local knowledge for environmental assessments and insisted on the philosophy, "It is your land, it is your project." Regular discussions were held, and local concerns were addressed through information sessions (Innavik Hydro 2020). • KEQC, a regional regulatory body, was crucial in project approvals. It ensured compliance with environmental and cultural safeguards specific to Nunavik's unique ecosystem and Indigenous heritage (Pituvik Landholding Corporation 2024). Pituvik leaders collaborated with Innergex to navigate these requirements. • Local youth and other community members were engaged in project planning, surveys, and operational roles. • Initial concerns from 17 percent of residents (Anselmi 2019) were effectively mitigated by educating the community on specific protective measures, particularly regarding water quality (Paradis 2023, Pituvik Landholding Corporation 2024).
Technology selection and procurement	• A run-of-river hydroelectric power system was chosen, to minimize environmental impact. The design avoids blocking water flow, addressing community concerns about salinity and biodiversity (Innavik Hydro 2021). • The project used engineering, procurement, and construction contracts, assigning the contractor design and construction responsibility. This approach streamlined logistics and ensured accountability for construction in the harsh northern environment (CIMA+ 2025).
Financing and permitting	• The project received public funding and private funding, including significant contributions from Innergex, and federal funding for Indigenous communities (Innergex Renewable Energy Inc. 2020). • KEQC's approval was essential, and conditions to mitigate impacts, including mercury-level monitoring, were required. Because the river is a community water source, stringent safeguards were required to maintain water quality during construction (Pituvik Landholding Corporation 2024).
Installation and commissioning	• Regularly scheduled community meetings facilitated direct communication between residents and project experts, who addressed questions, clarified project impacts, and provided timely follow-ups (Innavik 2024) to maintain transparency and build community trust. • Challenges included logistical issues, such as transporting materials by barge and airplane, and limitations due to COVID-19. To facilitate the build, a temporary bridge and access roads were constructed. Specialized logistics, such as a dedicated barge and plane, ensured timely delivery of materials and personnel (Rogers 2020, Innergex Renewable Energy Inc. 2020). • Local workers were prioritized for training and hiring, fostering a sense of ownership and pride in the project (Innergex Renewable Energy Inc. n.d.).
Operations	• Two local operators were trained to manage the system, fostering community ownership (Innavik Hydro n.d.). • Training and mentorship ensured operational sustainability. Further skill development programs, such as training in carpentry and mechanics, were also planned (Innavik Hydro n.d.).

This remote and predominantly Indigenous community faces challenges related to energy access and environmental sustainability. For decades, Inukjuak relied on diesel fuel for electricity, a solution fraught with ecological, economic, and logistical issues. The dependency on diesel posed significant risks to the environment and the population, including greenhouse gas emissions, high operational costs, fuel price fluctuations, and supply chain disruptions. Recognizing these challenges, the community sought a more sustainable and self-reliant energy solution.

Energy Transition Project Summary

The Innavik Hydro Project is a 7.5-megawatt (MW) run-of-river hydroelectric facility designed to replace diesel as the primary electricity source in Inukjuak. Operational since October 2023, the project was developed through a longstanding partnership between the Pituvik Landholding Corporation, the local Inuit landholding body responsible for managing Category I lands,[1] and Innergex, a private, renewable energy developer with extensive experience in hydroelectric systems. Pituvik played an instrumental role from the outset, ensuring that community values, environmental stewardship, and long-term economic benefits remained central to the project.

Financing covered approximately 75–85 percent of total development costs, with the remaining equity shared equally between Pituvik and Innergex (Perron-Piché 2023). Together, the partnership navigated regulatory approvals and addressed initial community resistance by proactively educating residents about protective environmental measures—particularly around water quality. The project positioned Inukjuak as a leader in Indigenous-led renewable energy development in northern Quebec. Table 4 gives a summary of the project.

[1] Category 1 lands are indigenous lands managed by First Nations under the First Nations Land Management Act, which allows greater autonomy and control over land use.

Key Findings

The Innavik Hydroelectric Project exemplified a community-driven initiative with a system that was selected to minimize ecological disruption, avoiding water flow blockage and biodiversity risks. Key interview findings, by project development phase, are summarized in Table 5.

Innavik Hydro's journey illustrates the transformative potential of Indigenous-led renewable energy projects guided by community-driven planning, culturally aligned partnerships, and robust environmental stewardship. While achievements included overcoming logistical complexities, navigating regulatory challenges, and addressing community concerns, ongoing efforts remain essential to sustain this progress. The following insights were summarized from the community interview process:

- Indigenous-led planning strengthens project relevance and accountability. The project represented an Indigenous-led renewable energy initiative that highlighted integration of Inuit traditional knowledge and local decision-making. Spearheaded by Pituvik leaders in collaboration with Innergex, the project navigated regulatory requirements through the KEQC, which enforced environmental and cultural safeguards for Nunavik's ecosystem.
- Transparent engagement builds trust and overcomes resistance. The project addressed initial resistance from 17 percent of residents (Paradis 2023) through education and inclusive engagement, empowering youth and locals in planning, surveys, and construction roles.
- Local resourcefulness turns logistical barriers into strengths. Logistical hurdles due to remote access, COVID-19 restrictions, and material transport were overcome by community resourcefulness, enhancing the community's project ownership.

As next steps, Pituvik and Innergex are:

- Committed to sharing lessons learned with other communities;
- Rigorously monitoring environmental impacts;
- Expanding capacity-building programs; and
- Reinvesting project revenues into community infrastructure and social programs.

This holistic approach provides a sustainable blueprint for renewable energy transitions in remote regions.

Honoring the Past, Powering the Future: The Kwanlin Dün First Nation's Energy Legacy

> "This project is about securing a future where our children and grandchildren don't have to rely on diesel—it's about building something lasting for the next generations."
>
> Chief Sean Smith, Kwanlin Dün First Nation

Kwanlin Dün First Nation (KDFN) is a self-governing First Nation of approximately 1,200 citizens located in and around Whitehorse, the capital of Yukon. The community experiences a subarctic climate characterized by long, cold winters and short, mild summers, which presents distinct challenges for reliable energy supply and infrastructure development. Historically, KDFN citizens relied heavily on the Yukon River for subsistence and cultural practices, but infrastructure developments such as the Whitehorse Dam (constructed in 1958) disrupted traditional ways of life and displaced many residents.

Today, despite their proximity to the territorial capital, the community faces ongoing energy challenges, including dependence on imported fuels during the winter months, vulnerability to fluctuating energy prices, and an isolated power system with limited local energy generation capacity. In 2005, the Kwanlin Dün First Nation became self-governing under its Final Agreement with the Yukon Territory and Canada, which set out KDFN's rights to land, resources, and governance. Since then, KDFN has advanced economic development through its business arm, Chu Níikwän Limited Partnership (CNLP). The Haeckel Hill–Thay T'äw Wind Energy Project builds on this strategic vision, reinforcing KDFN's position as a leader in Indigenous-led renewable energy development and local economic resilience.

Table 6. Summary of the Haeckel Hill–Thay T'äw Wind Energy Project

Project Details	Description
Technology	Wind energy (4 x EWT DW-61 1 MW turbines) (Eagle Hill Energy LP 2023)
Installed capacity	4 MW (two 2 MW wind farms); each wind farm is 2 MW to comply with Yukon independent power producer (IPP) size limits (Eagle Hill Energy LP 2023)
Timeline	2016 (initiation)–2024 (completion) (Eagle Hill Energy LP 2023)
Total cost	C$25,086,336 (~US$18 million) (Eagle Hill Energy LP 2023)
Funding sources	Investing in Canada Infrastructure Program, Clean Energy for Rural and Remote Communities Program, Canada Northern Economic Development Agency (Connors 2023, Government of Yukon 2023)
Project lead and key partners	KDFN, CNLP, Northern Energy Capital (CNLP 2024)
Ownership structure	100 percent Indigenous-owned by KDFN through CNLP (CNLP 2024)
Project impacts	• The project generates significant long-term revenue through electricity sales to Yukon Energy Corporation, reinvested into essential community infrastructure such as housing and roads (CNLP 2024). • The clean energy equivalent of over 615,000 liters of diesel was generated in the first year of energy production (personal communication with Stephanie Cunha, Yukon Energy Corporation, 27 June 2025). CO2 emissions are reduced by approximately 4,000 tonnes annually, totaling about 100,000 tonnes over the project's 25-year operational period (Connors 2023, EWT 2023, Environment Journal 2023). • KDFN has shifted from being displaced by energy projects (such as the Whitehorse Dam) to becoming a leader in renewable energy. Additionally, the project created local jobs and supported community empowerment and energy sovereignty (CNLP 2024).

Table 7. Interview findings on the Haeckel Hill–Thay T'äw Wind Energy Project, by project development phase

Project Development Phase	Key Findings
Planning	• Early engagement and structured partnerships were critical. KDFN leveraged its Modern Treaty Agreement to ensure decision-making power. Community engagement helped address skepticism from past wind project failures. The project aligned with Yukon's IPP policy, allowing First Nation ownership.
Technology selection and procurement	• The project selected EWT 1 MW turbines, for their suitability in remote Arctic conditions (WindpowerNL 2023). Regulatory approval was required for black turbine blades, which reduce ice buildup. Supply chain logistics and cold-weather adaptations were important factors in procurement decisions.
Financing and permitting	• Securing funding from federal sources, including the Canadian Infrastructure Fund, Natural Resources Canada, and the Canadian Northern Economic Development Agency, was essential (Government of Canada 2023). • The Yukon Environmental and Socioeconomic Assessment Board provided regulatory approval, ensuring environmental compliance (YESAB n.d.).
Installation and commissioning	• Construction was completed on schedule and under budget, allowing technological enhancements and new innovations to be added after construction completion. Local contractors were prioritized, strengthening regional workforce capacity. Some technical adjustments were required for turbine adaptation to a 60-hertz system, and blade heating–system performance was optimized during commissioning.
Operations	• The project faced challenges with wind variability, particularly in extreme cold. Blade heating technology is effective above -20°C but limited at lower temperatures.

Energy Transition Project Summary

The Haeckel Hill–Thay T'äw Wind Energy Project represents a significant milestone in KDFN's journey toward energy sovereignty. Located in the KDFN's Traditional Territory, this project benefits from the treaty's legal framework, which grants KDFN authority over land use planning, resource management, and economic development. Crucially, the treaty mandates that public utilities and government entities offer KDFN a minimum 25 percent equity stake in energy generation projects developed on their lands, ensuring meaningful economic returns, enhanced community control, and alignment with local priorities (Crown-Indigenous Relations and Northern Affairs Canada 2005).

Developed collaboratively by CNLP and Northern Energy Capital, the Eagle Hill Energy Limited Partnership is the first fully Indigenous owner of utility-scale wind power in northern Canada. This entity structured the project's financing, construction, and operations. This initiative not only reduces reliance on diesel and liquefied natural gas but also provides KDFN with sustained revenue, serving as a replicable model for Indigenous-led renewable energy development.

Key Findings

The Haeckel Hill–Thay T'äw Wind Energy Project progressed through several phases, each addressing technical, financial, and operational challenges. Table 7 lists the key findings, by project phase, summarized from interviews with the KDFN community and project partners.

The Haeckel Hill–Thay T'äw Wind Energy Project marks an historic transition for KDFN, demonstrating the community's capacity to own and operate renewable energy infrastructure and setting a strong precedent for Indigenous-owned economic development projects in the Yukon territory. The following are key lessons from the project.

Lessons for First Nations development corporations:

- Indigenous communities can now lead projects from the outset rather than wait for external developers.
- Energy development should be integrated into long-term economic planning to ensure alignment with community priorities.
- CNLP's governance structure remained nonpolitical, allowing the Haeckel Hill–Thay T'äw Wind Energy Project to maintain momentum and continuity despite a leadership change within KDFN following elections.

Lessons for utilities and developers:

- Public funding is critical for making wind projects viable in isolated grids.
- Energy storage solutions must be prioritized, to manage the intermittency of wind power.
- Collaboration between utilities, First Nations, and government agencies ensures smoother project integration and policy support.

This historic and innovative project offers a viable, replicable model for other First Nations. The following are ongoing or planned next steps for KDFN and other Indigenous communities in the Yukon:

- KDFN continues to expand its renewable energy portfolio, solidifying its leadership in sustainable development. Recognizing the importance of structured, equitable renewable energy growth, policy advocates are urging the development of an Indigenous-led power procurement framework to minimize intercommunity competition.
- To address intermittency and strengthen grid reliability, KDFN is strategically investing in a 20 MW capacity and 40 MWh energy storage system, reinforcing its commitment to proactive, sustainable, and community-centered energy independence.
- Yukon Energy Corporation is leveraging the project's success by evaluating larger-scale renewable initiatives, notably the proposed C$200 million Mount Sumanik Wind and Storage Project (Yukon Energy Corporation 2014, Eagle Hill Energy LP 2023).

3. United States Case Studies

Overview

The United States encompasses a wide variety of terrain, geographic features, and climate, and geographically isolated communities throughout the United States face unique challenges and opportunities related to energy transitions. Some communities face limited infrastructure and geographic isolation from population centers and electric grids, which necessitate innovative and tailored solutions for sustainable energy development. The three geographically isolated US communities selected for these case studies are located in Northwest Arctic Borough (NAB) (Alaska); Toro Negro, in Ciales municipality (Puerto Rico); and Borrego Springs (California). These communities are undertaking transformative energy projects to enhance their resilience and sustainability. These efforts were enabled by a mix of federal and state-level programs—such as the US Department of Agriculture's High Energy Cost Grants,

Department of Energy resilience funding, and California Energy Commission investments—alongside local leadership and nonprofit support. Additional details on enabling policies and funding structures for each project are provided in the Annex.

The NAB is subject to the harsh Arctic climate and is located a considerable distance from the electric grid. Its focus has been on harnessing local renewable resources to reduce reliance on costly imported fuels. This region's energy transition efforts reflect the NAB's broader strategy to integrate renewable energy sources, such as wind and solar, with existing energy generation systems, to ensure reliable and affordable power for its residents.

Toro Negro, Puerto Rico, presents a different set of challenges and opportunities. In the wake of devastating hurricanes, the community has turned to microgrid technology and solar power to rebuild and create a more resilient energy system. This transition is not just about recovery but also about establishing a sustainable energy infrastructure that can withstand future extreme weather events and reduce dependency on fossil fuels.

Borrego Springs, California, provides a noteworthy case of utility-led innovation in a geographically isolated desert community. Developed and operated by San Diego Gas & Electric (SDG&E), the smart microgrid was designed to improve reliability in a region served by a single transmission line. The system has enabled partial integration of local solar resources and provided backup power during planned outages, including public safety power shutoffs. While community members have expressed appreciation for the system's performance during those events, they have also voiced frustration with its limitations during unplanned outages. The project highlights both the opportunities and the complexities of deploying advanced grid technologies in rural and isolated settings—especially when community expectations and infrastructure realities are not fully aligned.

Together, these projects illustrate the diverse approaches and innovative solutions being employed across the United States to address the unique energy needs of geographically isolated communities.

The Power of Many: Northwest Arctic Borough's Collaborative Energy Transition in Shungnak and Kobuk

> "If a community wants clean energy, they need to ask themselves, 'Do we want control over our energy future? Do we want to lower costs?' It starts with getting everyone together, having a discussion, and making a plan. That's how this happened in Shungnak and Kobuk."
>
> Ingemar Mathiasson, energy manager, Northwest Arctic Borough

The NAB in Alaska encompasses an area of more than 39,000 square miles. It serves around 7,793 residents across the communities of Ambler, Buckland, Deering, Kiana, Kivalina, Kobuk, Kotzebue, Noatak, Noorvik, Selawik, and Shungnak (US Census Bureau 2020). This region is predominantly inhabited by Iñupiat people, whose way of life is deeply connected to the land and natural resources. The NAB is characterized by its geographically isolated location, challenging weather conditions, and reliance on expensive and environmentally unsustainable diesel fuel for power generation.

In recent years, the NAB has significantly reduced its dependence on diesel fuel by integrating renewable energy sources like wind and solar (Meadows et al. 2025, Anderson et al. 2023). This transition is closely tied to the communities' pursuit of self-determination and energy independence and the establishment of nonprofit IPPs. Historically, the region relied heavily on diesel generators, which are costly and environmentally unsustainable (Vera et al. 2020). In the early 2010s, feasibility studies and initial projects were conducted, to begin exploring alternative energy solutions, such as wind-diesel hybrid systems and solar PV installations (WHPacific 2010, Alaska Energy Authority 2014). By 2014, several communities had installed solar PV arrays to power essential infrastructure, such as water and sewer plants, reducing operational costs and diesel consumption (Uddin et al. 2023).

This case study focuses on the communities of Shungnak and Kobuk to gain a deeper understanding of the unique challenges and successes experienced by smaller, more geographically isolated communities in the NAB. These communities have leveraged renewable energy solutions to address critical issues such as geographic isolation, high energy costs, and environmental impact. Shungnak, with its declining population of approximately 247 residents as of 2024, has pursued solar PV and battery storage projects to reduce reliance on diesel. Similarly, Kobuk, with a population of approximately 156 in 2021, has adopted hybrid energy systems to power essential infrastructure while lowering operational costs and emissions.

Historically, Shungnak and Kobuk depended entirely on diesel generators for electricity. This reliance posed significant challenges, including high costs for fuel transportation, and environmental concerns related to emissions. In response, Shungnak embarked on an ambitious energy transition project. Although diesel-generated power costs have been partially offset by Alaska's Power Cost Equalization (PCE) program, which provides financial subsidies to reduce electricity expenses for rural residential customers, the subsidy does not cover all costs or fully address the instability tied to reliance on imported fuels (Alaska Energy Authority 2019). The persistent financial burden and vulnerability to external fuel supply disruptions underscored the critical need for transitioning to a more sustainable and locally controlled energy system.

Energy Transition Project Summary

The energy transition in Shungnak and Kobuk reflects how coordinated planning and existing infrastructure can enable innovative clean energy solutions in geographically isolated communities. The two villages are connected by a 10-mile electric intertie built in 1994 by the Alaska Village Electric Cooperative (AVEC). This connection made it possible to centralize generation in Shungnak while delivering power to both communities, laying the groundwork for shared benefit from new investments in renewable energy. Shungnak's first step came in 2016 with the installation of a 7.5 kW solar PV array to power the water treatment plant. Building on that early success, the community commissioned a much larger system in 2021—a solar and battery microgrid that includes a 223.5 kW solar array and a 352 kWh battery energy storage system (BESS). The project now offsets more than 9,800 gallons of diesel each year, demonstrating the power of local leadership, strategic partnerships,

and intercommunity collaboration to advance energy resilience in the Arctic (Anderson et al. 2023, NAB n.d.). Table 8 lists a short summary and impacts of the project.

Key Findings

The development and deployment of the solar and battery microgrid in Shungnak and Kobuk was the result of a deliberate, multi-phase process tailored to the unique conditions of rural Alaska. From early-stage planning to ongoing operations, each phase of the project combined community leadership, technical adaptation, and collaborative problem-solving. Table 9 lists key insights, by project phase, summarized from the interview process with the Shungnak and Kobuk communities.

The renewable energy transition in Shungnak and Kobuk exemplifies the potential of geographically isolated communities in Alaska to successfully shift away from diesel dependence toward sustainable and locally managed power systems. The following are key takeaways from the project:

- Strong local leadership drives project success. NAB and community leaders played a central role in keeping the project on track, coordinating across agencies, and ensuring alignment with local priorities.
- Early investment in workforce capacity pays off. Training local residents to operate and maintain the system reduced long-term reliance on outside contractors and built community ownership of the project.
- Partnerships must respect community timelines. Coordinating with funders, developers, and local governments required patience and flexibility, especially in geographically isolated settings where weather, freight schedules, and subsistence seasons shape timelines.
- Energy equity improves when projects are designed with cost savings in mind. By reducing diesel use, the project lowered fuel costs and stabilized power availability, creating tangible economic benefits for households and institutions.
- Success in one community creates momentum for others. The Shungnak-Kobuk model has inspired neighboring communities by illustrating the value of scalable, locally tailored renewable energy solutions in the region.

The following are planned and potential next steps for Shungnak and Kobuk:

- To build on their success, the communities plan to upgrade the inverter capacity, enabling full utilization of the existing 352 kWh battery system and maximizing energy efficiency.
- Further expansion of the solar array capacity will lead to additional reductions in diesel use and greater economic benefits.
- Continued investment in community capacity building is essential, including advanced training for local operators in energy systems management.
- Proactively sharing insights and lessons learned from the project with neighboring geographically isolated communities will foster similar renewable transitions throughout the region.
- Finally, using a portion of project revenues to establish a dedicated maintenance and repair fund will ensure long-term operational sustainability, reinforcing a replicable model for energy independence, economic growth, and environmental stewardship across rural Alaska.

Table 8. Shungnak and Kobuk project summary

Project Details	Description
Technology	Solar PV bifacial panels, BESS, inverter, microgrid controller
Installed capacity	Solar PV: 223 kW BESS: 352 kWh
Timeline	January 2020—December 2021
Total cost	US$2.3 million
Funding sources	US Department of Agriculture High Energy Cost Grant: US$1,219,675 Northwest Arctic Borough Village Improvement Fund: US$800,000
Project lead and key partners	AVEC Alaska Native Renewable Industries Ageto (microgrid controller provider) Blue Planet Energy (battery provider)
Ownership structure	The project is structured as an IPP owned and operated by the tribal entities of Shungnak and Kobuk. The IPP sells power to AVEC under a Power Purchase Agreement. Revenues are used to maintain the system, cover operational costs, and provide economic benefits to the communities.
Project impacts	• The project improved quality of life through quieter operation during diesel-off periods, reducing noise pollution. • Community ownership of energy resources was strengthened, fostering a sense of empowerment and self-reliance. • Reduced diesel fuel consumption has lowered energy costs, reduced greenhouse gas emissions, and created a revenue stream for the community through the IPP model. • The project generates approximately US$100,000 annually in net revenue, which is reinvested in the community. • Less diesel fuel needs to be transported, reducing risks of spills and pollution. • The project has met or exceeded expectations by achieving 11 percent renewable energy penetration, offsetting diesel consumption, and generating revenue to fund community projects like heat pump installations.

Source: Table information from Anderson et al. (2023) and Meadows et al. (2025).

Table 9. Interview findings on the Shungnak and Kobuk systems, by project development phase

Project Development Phase	Key Findings
Planning	• The establishment of an IPP allowed the community to maintain ownership and reinvest revenue from power sales. • Shungnak's renewable energy potential was carefully assessed during the planning phase. Solar energy was identified as a viable resource. Although the seasonal variability of solar energy posed challenges, the system was designed to prioritize solar input during peak availability while relying on minimal diesel backup during darker months.
Technology selection and procurement	• The project utilized bifacial solar panels, which capture sunlight on both sides for increased efficiency. The panels were installed in a semicircular configuration to optimize energy capture throughout the day, adapting to Alaska's unique solar conditions, such as low sun angles and extended daylight during summer. • Challenges encountered during the procurement process included system compatibility issues. Some components, such as SolarEdge optimizers, initially experienced higher-than-expected failure rates. These issues were resolved through technical troubleshooting and adjustments. • Installation on the tundra presented unique challenges. The system design allowed for shifting permafrost by using specialized racking to ensure stability despite ground movement.
Financing and permitting	• The Shungnak energy project required careful alignment with the PCE program to maximize its financial benefits for the community. • To meet federal requirements, the project underwent a National Environmental Policy Act determination under US Department of Agriculture guidelines. The review was completed without significant delays, clearing the way for construction. • The financing for the project was a combination of federal and local funding. The creation of an IPP enabled the community to generate revenue by selling renewable energy to AVEC under a Power Purchase Agreement. The income from power sales is reinvested into system maintenance, operational costs, and community development. • Land use agreements were addressed in the permitting process. The city of Shungnak provided the land for the solar arrays and microgrid infrastructure, leasing it to the tribal IPP under a formal agreement.
	• The project team collaborated with AVEC to ensure the renewable energy system's seamless integration into the existing diesel-based grid. This collaboration also ensured compliance with PCE requirements and avoided disruptions to the community's energy cost savings.
Installation and commissioning	• Shungnak's geographically isolated location and extreme arctic conditions presented installation challenges. Piles had to be driven into the permafrost, and specialized racking systems were used to address shifting tundra. Despite these challenges, the project was completed efficiently, with minor adjustments to the original design. • Each component, including the batteries (by Blue Planet) and the microgrid controller (by Agito), was tested and calibrated to ensure seamless operation. AVEC facilitated the final commissioning to integrate the system into the existing grid. The project experienced a slight cost overrun, requiring an additional US$200,000, which the Village Improvement Fund covered.
Operations	• The project is maintained by a local workforce and geographically isolated monitoring systems. AVEC continues to provide operational oversight while tribal operators contribute to day-to-day maintenance. • Tribal members have been trained to manage routine operations, such as monitoring battery performance and ensuring the microgrid's stability. Additional training addresses issues like racking adjustments due to permafrost shifts. • The project has fostered local capacity by employing and training tribal members in energy system operations. Existing AVEC utility operators also handle some maintenance, creating a dual-system management structure that increases reliability.

Source: Table information from Anderson et al. (2023) and Meadows et al. (2025).

Unleashing Potential: Overcoming Challenges in the Borrego Springs Microgrid

> “Borrego Springs is unique because we are landlocked—our only power line runs through a state park. That makes energy resilience not just a goal, but a necessity.”
> —John Peterson, Borrego Springs Sponsor Group

Borrego Springs, California, is a small, unincorporated community located in the heart of Anza-Borrego Desert State Park, California’s largest state park, known for its stunning desert landscapes and star-filled night skies. The community has a population of about 3,500 residents (Census Reporter 2022). The state park plays a critical role in the town’s identity and economy. It attracts 650,000 to 1 million visitors annually, making tourism the primary economic driver for the community (County of San Diego 2011, 5–6). Residents benefit from the park’s unique environmental and cultural significance. It is home to thousands of archaeological sites tied to the heritage of the Cahuilla and Kumeyaay peoples. Its preservation ethos influences local development and infrastructure decisions. Borrego Springs’ economy also caters to retirees and seasonal visitors, with services such as hotels, restaurants, and recreational facilities (County of San Diego 2011, 6–9).

Borrego Springs experiences frequent power outages due to its exposure to extreme weather events such as wildfires, high winds, flash floods, and lightning strikes. These risks are compounded by the community’s location at the end of a single transmission line operated by SDG&E, which makes the energy supply especially vulnerable to disruption (Katmale et al. 2019).

Table 10. Borrego Springs project summary

Project Details	Description
Technology	Solar PV, BESS, ultracapacitor, conventional generator
Installed capacity	26 MW PV array (non-utility-owned) 8.6 MW rooftop PV (non-utility-owned) 500 kW/1.5 MWh battery 1 MW/3 MWh battery 250 kW ultracapacitor 4.4 MW generator 7.3 MW/14.6 MWh battery (commissioning)
Timeline	Initial planning began in 2008; significant components were operational by 2013. Upgrades are ongoing (Katmale et al. 2019).
Total cost	US Department of Energy (DOE): US$6.1 million California Energy Commission: US$6.9 million Additional DOE funding: US$4.5 million SDG&E cost-sharing not disclosed in detail (Katmale et al. 2019)
Funding sources	DOE, California Energy Commission, SDG&E
Project lead and key partners	SDG&E, with support from the California Energy Commission and DOE
Ownership structure	Utility-owned
Project impacts	• Economically, the microgrid has provided improved reliability during planned outages, particularly public safety shutoffs, but many residents still experience unplanned service disruptions, leading to mixed perceptions about the microgrid's impact on tourism and local economic stability. While the project supported utility-sector employment and regional development in renewable energy, community members have voiced concerns that direct job creation within Borrego Springs itself has been limited (Katmale et al. 2019). • In addition to enhancing resiliency during planned outages, the microgrid aims to decrease reliance on imported electricity generated with carbon-based fuels, by incorporating local generation and storage. While these developments have the potential to reduce energy costs, concrete evidence of such savings for the community is not yet available, and some residents have expressed concerns regarding the equitable distribution of benefits (Barabino et al. 2023). • While the microgrid's advanced design has reduced reliance on diesel generators, community perceptions of its effectiveness have not been fully favorable.

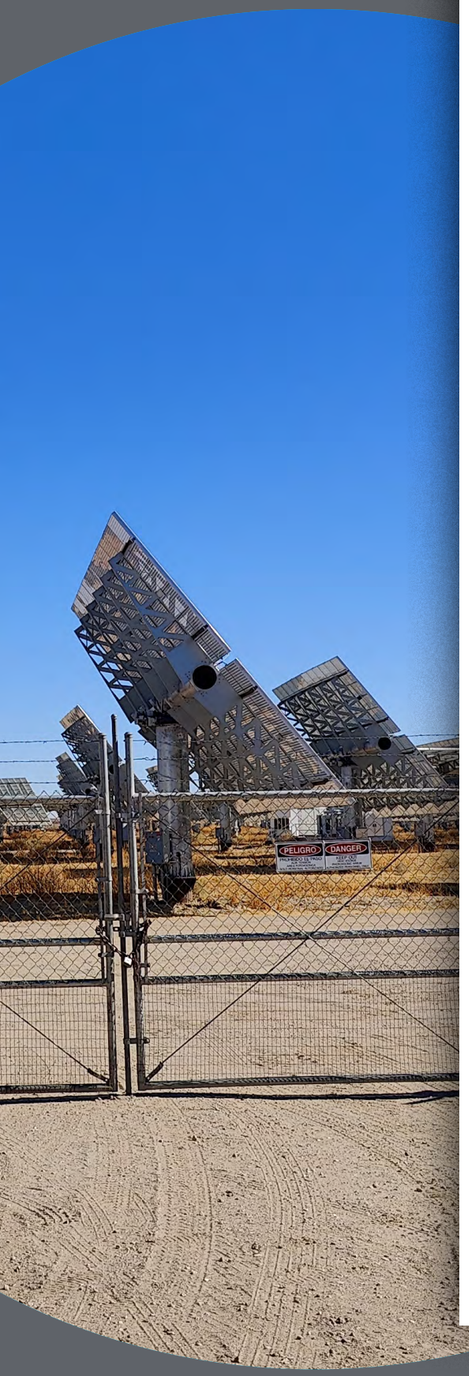


Table 11. Borrego Springs interview findings, by project development phase (Part 1)

Project Development Phase	Key Findings
Planning	Limited community engagement during the utility planning process led to overlooked local concerns, including strong and sustained opposition to an earlier SDG&E proposal to expand transmission lines through Anza-Borrego Desert State Park. Although the route was ultimately changed, this episode continues to influence community trust in utility-led projects.
Technology selection and procurement	The technology for the Borrego Springs Microgrid was selected to meet the specific operational challenges of maintaining energy service in a geographically isolated desert environment. The system design reflects a blend of traditional and advanced technologies tailored to extreme weather, limited transmission access, and the need for islanding capability. System integration was constrained by technical limitations and strong community resistance to expanding infrastructure through protected parklands, reflecting environmental and cultural priorities. Key technical components are the following: **Energy Storage Systems:** • 500 kW/1.5 MWh battery • 1 MW/3 MWh battery (currently the island master/grid-forming asset) • 250 kW ultracapacitor (supports short-duration smoothing) • 7.3 MW/14.6 MWh battery (currently being commissioned to replace the 1 MW battery as island master) • 4.4 MW conventional generator (recently added to support system reliability during outages) **Solar Generation:** • Although a 26 MW utility-scale solar PV system is located nearby, it is privately owned (now by Clearway) and is not part of the microgrid. SDG&E previously had limited access to a few inverters, but this resource is no longer used, due to switching complexity. • About 8.6 MW of rooftop PV exists in the community; however, these systems are not utility-controlled and cannot be coordinated during islanded microgrid operations. **Procurement Considerations:** • The microgrid assets were procured to meet grid-forming, load-balancing, and black-start capabilities. Initial procurement focused on proving microgrid functionality in staged outages and limited islanding scenarios.
Financing and permitting	Securing funding and navigating permitting requirements were crucial milestones in the development of the microgrid. The project was supported by substantial grants (Table 10). While SDG&E navigated complex regulatory and permitting processes, some community members have expressed that community engagement was limited or reactive. The project illustrates the challenges of aligning technical development with proactive, inclusive communication—especially in geographically isolated communities.

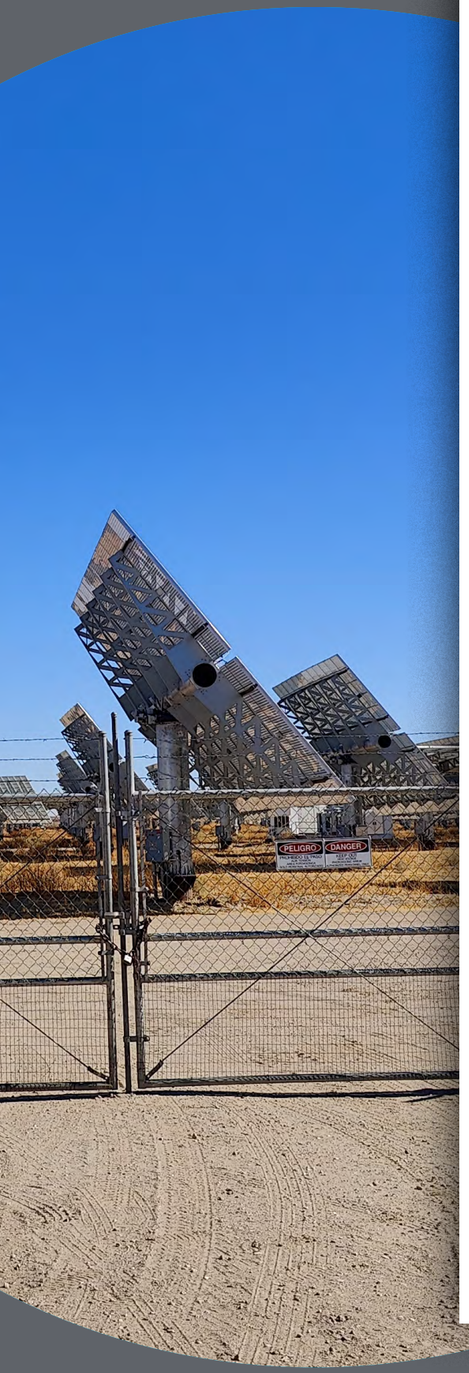


Table 11. Borrego Springs interview findings, by project development phase (Part 2)

Project Development Phase	Key Findings
Installation and commissioning	The installation and commissioning of the Borrego Springs microgrid required retrofitting existing infrastructure to accommodate a hybrid mix of solar, battery storage, and conventional generation technologies. The project unfolded in stages, beginning with the integration of early storage assets and culminating in the recent commissioning of a 4.4 MW generator and the staged integration of a new 7.3 MW/14.6 MWh battery system. Key challenges during installation included: • **System Integration:** Coordinating legacy infrastructure with new grid-forming and load-balancing technologies required tailored engineering solutions and phased testing. This included configuring real-time controls across the microgrid's various components. • **Environmental and Site Constraints:** Extreme desert temperatures and site access limitations added complexity to the installation timeline. System components were selected and installed with durability and geographically isolated operability in mind. • **Commissioning Process:** Initial battery and ultracapacitor systems were brought online alongside existing backup generation. The commissioning of the 7.3 MW/14.6 MWh battery—expected to become the new island master—is currently underway and scheduled for completion in the third quarter of 2025. While the technical commissioning was completed successfully for earlier phases, full microgrid functionality—especially seamless islanding during unplanned outages—remains a work in progress. The utility expects commissioning of the new battery to significantly expand the system's capability, providing more-robust frequency control and grid-forming services (Katmale et al. 2019, SDG&E 2024).
Operations	• While the system has demonstrated functionality during some planned outages, its performance during unplanned events has varied. These inconsistencies are primarily attributed to communication and control issues between system components during grid disturbances. • The microgrid's ability to fully serve the community during islanded conditions is still evolving. Operational protocols continue to be refined, particularly in preparation for integrating the new long-duration battery as the primary grid-forming asset. Once fully commissioned, this battery is expected to enhance frequency and voltage stability and participate in the California Independent System Operator market during normal grid conditions. • Community stakeholders stressed that the core value of the microgrid lies in its ability to operate independently during outages, and that enhancing local resiliency—not increasing interconnection—should remain the project's priority. • Some residents have expressed frustration that the microgrid has not consistently performed during unplanned outages, reinforcing a perception that reliability has not substantially improved.

Energy Transition Project Summary

In response to persistent energy reliability challenges, SDG&E led the development of the Borrego Springs microgrid, supported by substantial public funding. Although a 26 MW solar PV array is located nearby—originally developed by NRG and now owned by Clearway—it is not part of the operational microgrid. SDG&E previously had limited access to several inverters at the site for grid support, but that arrangement is no longer active. Instead, the microgrid operates using utility-managed assets, including a 500 kW/1.5 MWh battery, a 1 MW/3 MWh battery, a 250 kW ultracapacitor, and a recently commissioned 4.4 MW generator. Approximately 8.6 MW of rooftop solar also exist within the community but are not utility controlled. A new 7.3 MW/14.6 MWh battery, once fully commissioned, will become the primary grid-forming asset. Community involvement during the project's initial planning phase was limited, contributing to ongoing concerns about transparency, decision-making authority, and alignment with local priorities. Table 10 gives a project summary and lists project metrics and impacts.

Key Findings

The Borrego Springs microgrid in Southern California represents one of the earliest utility-led efforts in the United States to enhance energy resilience in a geographically isolated, high-risk environment. Developed and operated by SDG&E, the project integrates solar, battery storage, and legacy diesel systems to serve a desert community frequently impacted by outages and climate events, like wildfires, that damage energy infrastructure. The development of the microgrid involved a complex mix of technical innovation, environmental considerations, and regulatory

navigation. Table 11 outlines key interview findings across each phase of the project, shedding light on both achievements and challenges, particularly around community engagement and system performance.

The following lessons were learned after consulting with the Borrego Springs community and studying their microgrid energy project:

- Storage must match the promise. Limited backup duration has prevented the microgrid from meeting reliability expectations.
- Prioritize local resilience over transmission expansion. While some technical experts point to transmission constraints as barriers to solar integration, community members stressed that improving microgrid performance—through enhanced storage and islanding capability—is more important than adding new transmission infrastructure.
- Trust hinges on early engagement. Lack of inclusive planning contributed to community distrust.
- Environmental context must guide infrastructure planning. Community opposition to earlier proposals to expand transmission through protected parklands illustrates how past development efforts continue to shape local attitudes toward infrastructure and conservation.
- Local capacity matters. Without a community-driven energy plan, residents remain sidelined in shaping their energy future.

Despite notable progress in grid improvements, and several successful planned outages demonstrating the microgrid's potential to power all of Borrego Springs, challenges remain. Two community members representing local nonprofit organizations expressed dissatisfaction, citing instances where the microgrid did not operate as intended during unplanned outages. These disruptions—largely attributed to communication issues between the microgrid controller and the system's frequency response—have contributed to ongoing skepticism about reliability. While the project has advanced technical understanding of solar-plus-storage islanding systems, continued research and refinement are needed to address voltage and

frequency stabilization—critical concerns as California moves toward increased renewable energy adoption.

This case highlights the importance of distinguishing between technical achievements and lived community experience. While the microgrid represents a significant utility-led innovation, some Borrego Springs residents remain concerned about the lack of tangible local benefits, and inadequate community involvement in key decisions.

Moving forward, priority actions may include:

- Expanding local storage to support more-robust islanding capability;
- Exploring non-wired solutions to grid transmission functions that respect conservation boundaries; and
- Deepening local engagement to align energy strategies with community goals and values.

Solar Survivors: Toro Negro's Light After the Storm

> "With all the pros and cons, and with all the hardships and successes we've had within the project, we believe that it has been an entirely beneficial project for our community and regardless of the outcome, it will always be an asset acquired by this community through its effort and commitment."
>
> José Figueroa, Toro Negro community leader

Toro Negro is a small community of 62 inhabitants within the municipality of Ciales, nestled in the central mountainous region of Puerto Rico. Located in the Toro Negro State Forest, this area is characterized by its lush, tropical vegetation and diverse ecosystems, including cloud forests and mountainous regions. The rough terrain features steep slopes and a network of rivers and streams that contribute to the island's hydrological system.

The local economy is centered on small-scale agriculture, with coffee cultivation being a significant activity, alongside subsistence farming of root vegetables and fruits. Community members also engage in traditional crafts, such as weaving and woodworking, and some contribute to ecotourism initiatives, given the area's proximity to hiking trails and natural attractions like waterfalls. Toro Negro's cultural identity is deeply tied to its rich environmental heritage and agricultural traditions. Additionally, Toro Negro stands out as a tight-knit community where members understand the importance of relying on each other. They also have a generous attitude and enjoy sharing their experience with their PV and BESS project.

The prolonged electricity blackout caused by Hurricane Maria in 2017, which lasted 8 months, highlighted the urgent need for more-reliable power in Puerto Rico, especially for mountainous rural communities that experienced inconsistent electricity even before the hurricane.

Energy Transition Project Summary

Recognizing the critical need for a resilient energy source, the community took the initiative to develop a solar microgrid, which was the first of its kind in Puerto Rico. This effort was spearheaded by community leader José Figueroa and was supported by the Community Foundation of Puerto Rico (Fundación Comunitaria de Puerto Rico—FCPR) and Somos Solar, which donated the required financial resources for the PV and BESS installations. In March 2018, Toro Negro established Puerto Rico's first community solar microgrid, providing power to all 28 households and a community center through a decentralized network of 20 PV and battery storage systems. The unique design, tailored to the community's topography, includes easily dismountable rooftop PV panels and underground electrical connections, providing resilience against future storms and high-speed winds (Deng et al. 2019). Because of its islanded setup, the microgrid can provide reliable power even when the main grid is compromised. A summary of the project and its impact on the community is given in Table 12.

Thirteen of the twenty installed systems provide energy to single houses, six systems can provide energy to two houses, and one system can provide energy to three houses. Each household has a meter to measure energy consumption and a transfer switch in case they want to connect to the main grid. Six systems have the capability to export energy to the Puerto Rico grid; however, current regulations—administered through the Puerto Rico Energy Bureau and the utility operator LUMA—do not allow net metering for cases in Toro Negro where more than one household is connected to PV (Deng et al. 2019). As a result, most systems remain electrically interconnected but do not actively inject power into the grid. Their primary function is to supply power directly to homes—particularly during outages—rather than to maximize economic returns. There is also no access to historical energy generation data, which makes it even more difficult to estimate tariffs or calculate return on investment. The system was designed for resilience and community benefit rather than financial payback.

Maximo Solar was the company responsible for building the microgrid, and SunSol LLC was the supplier. SunSol currently charges a monthly fee of US$735 for basic maintenance of and administrative services for all systems (personal communication with José Figueroa, community leader of Toro Negro, 31 May 2025).

Table 12. Toro Negro project summary

Project Details	Description
Technology	Solar and storage microgrid
Installed capacity	PV: 83 kW (alternating current) BESS: 116 kWh (Deng et al. 2019, FCPR 2019)
Timeline	Hurricane Maria hit the island in September 2017, and the subsequent electricity outage lasted 8 months. The electricity was restored on 25 May 2018 (FCPR 2018), and in August 2018 the PV and BESS units were online (Comunidad Toro Negro 2024).
Total cost	More than US$400,000 (East Penn Manufacturing 2020).
Funding sources	FCPR and Somos Solar
Project lead and key partners	Key partners: José Figueroa, Comunidad Toro Negro, FCPR, and Somos Solar
Ownership structure	Comunidad Solar Toro Negro owns all the systems.
Project impacts	• While initial energy costs dropped compared to the national grid, the microgrid now operates at a financial loss due to insufficient revenue. Job creation was limited to the installation phase, with ongoing maintenance outsourced to external entities, offering minimal local employment benefits. Despite energy autonomy in power generation, dependence on external companies for system management hinders true independence, underscoring challenges in long-term sustainability. • The transition to solar energy eliminated reliance on fossil fuel generators. By avoiding large-scale infrastructure like power lines, the project preserved local biodiversity and minimized habitat disruption in Toro Negro's ecosystems. • Community-led microgrid governance strengthened local cohesion and pride. Residents gained hands-on experience with renewable systems, boosting awareness of sustainable practices.

Table 13. Toro Negro interview findings, by project development phase

Project Development Phase	Key Findings
Planning	• Initiated after Hurricane Maria to address urgent energy needs, the project was led locally by community leader José Figueroa, with institutional support from FCPR and Somos Solar. This collaborative effort prioritized post-storm resilience, ensuring basic electricity for homes and essential services. • Integration challenges arose due to the incompatibility of the project with Puerto Rico's net metering framework.
Technology selection and procurement	• Solar PV and BESS were selected for their modularity, reliability, and suitability for geographically isolated areas, allowing for efficient installation and maintenance. This approach allowed the community to achieve energy independence after Hurricane Maria, addressing its urgent needs for reliable electricity. • The decentralized configuration reflects a focus on resilience, providing flexibility and redundancy across the system. • The technology choice underpins the community's capacity to manage energy solutions effectively and set an example for other rural areas seeking sustainable energy independence.
Financing and permitting	• The community received the equipment as a donation from FCPR and Somos Solar. • Shortly after the microgrid was installed in Toro Negro, the Regulation on Microgrid Development of the Puerto Rico Energy Commission (Regulation 9028) was published, in May 2018. By September of the same year, Comunidad Solar Toro Negro complied with the requirements to be registered and certified before the Regulatory Board of Public Service of the Government of Puerto Rico.
Installation and commissioning	• The installation was performed by Maximo Solar.
Operations	• The governance of Toro Negro's microgrid is managed by a board of directors, elected in 2019, which currently has four sitting members. Community members volunteer their time to be part of the administration. • Technical expertise is needed within the community, as it currently relies on external support for maintenance and diagnosis beyond members' knowledge. Community members can provide basic troubleshooting; however, if further technical support is needed, they must pay a US$250 fee for a technician to come to the community to check their system. • The current microgrid manager (SunSol) charges a global fee of US$735 per month and provides maintenance of solar panels and batteries, meter reading, billing, and monthly payment collection.

Key Findings

The Toro Negro microgrid in Puerto Rico, developed after Hurricane Maria to address urgent energy needs, is the first community-managed solar microgrid on the island. Though the microgrid faces challenges integrating with Puerto Rico's centralized grid and net-metering policies, it continues to operate, showcasing the community's leadership and commitment to sustainability. Governance is managed by the nonprofit Comunidad Solar Toro Negro, which emphasizes community engagement, equitable tariffs, and transparent operations. The close-knit community's qualities of trust and cooperation were essential for the microgrid's success. However, maintenance relies on external technical support, and insufficient revenue poses challenges for sustainability. Key interview findings, by project development phase, are summarized in Table 13.

Despite difficulties, the microgrid continues to operate, a testament to the community's leadership, adaptability, and commitment to sustainability. This pioneering project has empowered Toro Negro to maintain energy autonomy, proving the strength of its organizational capacity and setting a precedent for other community-led renewable energy initiatives in Puerto Rico and beyond. The project highlights how localized leadership, combined with institutional frameworks, can create impactful, lasting solutions even in the face of significant challenges. Several key lessons can be summarized from consultations and interviews with the Toro Negro community:

- The success of the Toro Negro microgrid shows the importance of strong leadership and community involvement in project planning, implementation, and governance.
- Transparent, robust, and inclusive governance structures have been essential for maintaining operations and resolving challenges within the community framework.
- Despite operational success, the project highlights the difficulty of achieving financial sustainability in rural energy initiatives without external subsidies or additional income streams.
- While the project has empowered the community, reliance on external entities for maintenance and technical expertise underscores the need for local capacity building. There is a clear need for ongoing technical training and community education, to enhance self-reliance and reduce dependency on external support.

- The decentralized setup, while resilient, has revealed inefficiencies in energy distribution and challenges in connecting multi-residence systems to the grid without risking energy accounting issues. The inability to fully leverage net metering, due to design limitations, has reduced the system's potential efficiency and profitability.
- Despite collecting usage data and implementing a standardized rate per kilowatt-hour, the operational costs continue to be higher than the generated income.

Toro Negro's experience highlights the importance of community involvement, robust governance structures, and continuous support from external organizations. Recommendations and next steps for the community include the following:

- Seek additional funding sources or subsidies to offset operational costs and to repair systems that are currently not operational. Engage with policymakers to ensure continued support for community-led energy initiatives.
- Prioritize gathering detailed data on current system performance and costs, to refine the microgrid design and ensure that new funding is utilized effectively for long-term sustainability.
- Develop and implement training programs, to equip community members with the technical skills needed for system maintenance and troubleshooting. Investigate the potential for transitioning certain maintenance responsibilities from external entities to local stakeholders.
- Address technical issues related to energy distribution inefficiencies and multi-residence systems, to improve integration with net metering. Advocate for regulatory adjustments to make microgrids more compatible with existing energy infrastructure and to incentivize rural renewable energy projects.
- Investigate the feasibility of an online billing system.
- Create a long-term strategy for adapting to changing energy needs and environmental conditions.

4. Mexican Case Studies

Overview

The selected Mexican communities were part of a federal program dedicated to providing electricity access to populations that still lack it, under the concept of energy justice to reduce energy poverty[2] in the country. The Mexico Secretariat of Energy (Secretaría de Energía—SENER) has provided funding for the electrification of rural and marginalized urban areas through the Universal Electric Service Fund (Fondo de Servicio Universal Eléctrico—FSUE) since 2017 (SENER 2017).

The management and implementation of the program, including conducting outreach, candidate selection, and project execution, is handled by SENER through the Federal Electricity Commission (Comisión Federal de Electricidad—CFE) with National Bank of Public Works and Services (Banco Nacional de Obras y Servicios Públicos, S.N.C.—Banobras) serving as the trustee of the FSUE. In one of its modalities, the program finances the installation of renewable solutions, which includes isolated PV and BESS for communities that have no electricity and for which the main grid is more than 5 kilometers (km) away. The selected case study communities benefited from the FSUE in this form. They belong to the states of Sonora, Tamaulipas, and Veracruz. These communities had no existing electricity access, as they are located in areas where grid extension is not technically or economically feasible. These projects were made possible through the FSUE, created under the 2013 Energy Reform and mandated by Mexico's Electricity Industry Law to reduce energy poverty in underserved communities. The program reflects national goals for social equity and sustainability through public investment in off-grid electrification. In early 2025, the FSUE was updated to expand its catalog of eligible energy solutions—now including distributed generation, self-consumption systems, and isolated solar systems—allowing for more-flexible approaches tailored to local conditions. Additional details on FSUE's legal foundation and structure are provided in the Annex.

[2] Defined in the Energy Planning and Transition Law as the situation in which households cannot satisfy basic energy needs given low income or social deficiencies (Art. 3, Fracc. XXI). Energy justice is then defined as actions oriented to reduce energy poverty (Art 3. Fracc. XVI).

Unlike other regions in Canada and the United States analyzed in this report, where implementation and funding strategies vary, projects in Mexico are centrally funded through SENER via the FSUE. This centralized model ensures consistency in funding, technology selection and project management, with all phases coordinated by the CFE. Key aspects such as financing, permitting, and standardized technology use are discussed in Section 4.2, as they remain consistent across all FSUE projects. Sections 4.3–4.5 focus on the localized impacts and specific challenges for the remote, off-grid communities selected as case study locations, where stand-alone PV systems were installed.

Federal Approaches to Expanding Off-Grid Energy

The FSUE aims to contribute to reducing energy poverty by providing infrastructure that supplies electricity access for domestic users who do not yet have electric service and supplying efficient equipment and technologies that use renewable energy for basic needs, such as food preparation, refrigeration, water heating, and lighting, among others. Through these actions, the FSUE helps meet basic energy requirements in rural communities and marginalized urban areas. However, to do so, mechanisms must be implemented to monitor the operation of the installed equipment and systems and to provide maintenance to the extent possible.

To support the electrification of underserved and remote communities in Mexico, the FSUE facilitates grid expansion and the deployment of decentralized renewable energy systems such as solar PV, with priority given to rural and Indigenous populations. This report only focuses on the installation of decentralized renewable energy systems and does not address grid expansion. All systems are off-grid and not interconnected to the national electricity grid; net metering does not apply. The FSUE operates through a transparent framework that includes proposal submission and project prioritization based on social impact and cost-effectiveness. Key partners, including the CFE, municipalities, and private entities, collaborate to implement projects that reduce energy poverty, improve living conditions, and increase the likelihood of long-term sustainability through standardized technologies, community training, and performance-based contractor obligations. The FSUE application process is summarized in Figure 1.

Figure 1. Process for FSUE applications

Source: Personal communication with Antonio Alcaraz, Ociel Ong Rubio and Juan Pablo González of CFE, 6 September 2024.

Planning, Technology Selection, and Procurement

The reasoning behind using small, isolated solar PV systems for rural electrification is rooted in their practicality, cost-effectiveness, and ability to meet basic household energy needs (Opiyo 2020). These types of systems are specifically designed to provide essential services like lighting and charging small appliances, addressing the immediate energy requirements of underserved communities (Kabir et al. 2017). Additionally, their ease of installation and minimal maintenance requirements make them ideal for remote areas with challenging infrastructure and reduced access to technical support.

To determine sizing, SENER opted for a universal solution, given the lack of available electrical consumption data and the expense and time associated with gathering detailed information. Furthermore, the constantly changing demographic composition of many localities—driven by rural-urban mobility and migration patterns—renders existing data volatile and hard to interpret (FAO 2018). The specific criteria and sizing assumptions adopted by SENER for the three projects analyzed are summarized in Table 14 (SENER 2018a; see also Flores-Espino et al. 2021). It is worth noting that these guidelines applied specifically to the three projects analyzed here. Future projects will follow the updated framework established under the 2025 Law of the State-owned Enterprise, Federal Electricity Commission (Ley de la Empresa Pública del Estado, Comisión Federal de Electricidad) (Secretaría de Gobernación 2025). At the beginning of the program, the minimum capacity for residential systems was 300 W; however, as of 2024, this minimum capacity increased to 550 W. For projects involving productive uses of electricity, community meeting centers, and/or small "health centers," the minimum required capacity is 1,200 W.

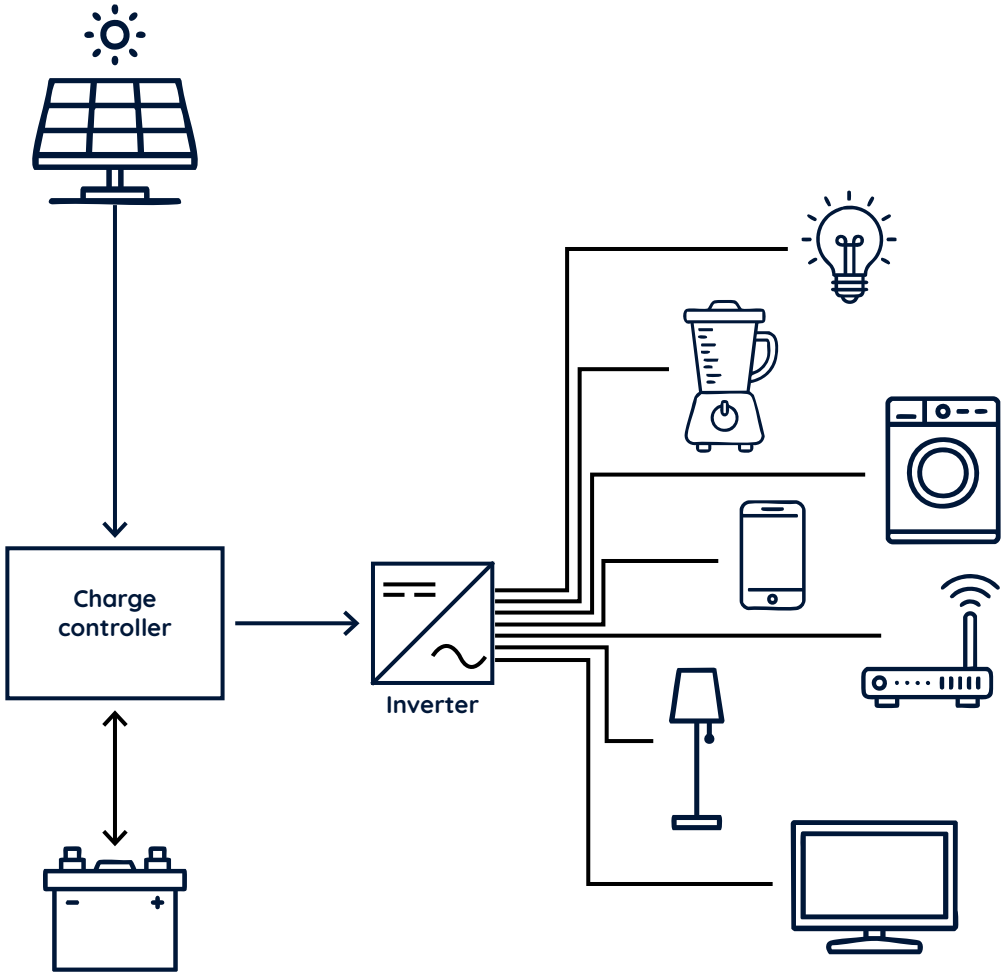
In each community, households self-selected to participate in the project by submitting basic documentation, such as identification and proof of residence. Community leaders and supporting organizations helped compile the applications into a collective submission to the CFE. If the project was approved, all eligible households that applied received a PV and BESS. As a result, the final number of installed systems reflects the subset of the community that completed the application process, rather than the entire population.

Contractors for the project were selected through a competitive bidding process and varied for each community or region. The selection criteria focused on technical and quality standards while ensuring compatibility with the needs of remote, off-grid installations. The selected vendor provided not only the hardware but also user manuals and training sessions for residents on how to use the systems. Vendor

contracts are not always standard, allowing for differences between the services and systems provided by the contractors while maintaining minimum requirements.

The installed systems for each community are listed in Table 15, and a representation of the typical electrical devices and appliances used in residential buildings is shown in Figure 2. Table 16 presents the individual system costs for each type of installation, namely residences, community centers, schools, and health centers.

Figure 2. Typical devices and appliances found in Mexican communities after electrification



Source: Personal communications with the CFE and community members, 2024.

Table 14. Assumptions to determine PV and BESS sizing for each type of building under the FSUE

Parameter	Type of Building			
	Residential	School	Health Center	Community Center
Building characteristics	Living/dining room, kitchen, and two rooms, 48 square meters	Two classrooms	One examining room and one waiting room	Unspecified
Estimated consumption	Minimal daily consumption of 750 Wh	2,300 Wh, 5 days a week	4,000 Wh, 1 day per week	Minimal daily consumption 1,000 kWh
Minimal solar panel capacity	300 W	900 W (3x300 W)	1,200 W (4x300 W)	1,200 W (4x300 W)
Average daily generation	1,320 kWh	3,960 kWh	5,280 kWh	5,280 kWh
Inverter capacity	1,200 W	1,200 W	1,200 W	1,200 W
Electrical infrastructure provided in addition to complete PV and BESS	Four light fixtures, two electrical outlets, two switches, cabling, connectors, and the required protections	Five light fixtures, four electrical outlets, five switches, cabling, connectors, and the required protections	Five light fixtures, four electrical outlets, five switches, cabling, connectors, and the required protections	Five light fixtures, four electrical outlets, five switches, cabling, connectors, metering capabilities, and the required protections
PV panel life	>10 years*			
BESS life	Change every 4 years**			

Source: SENER (2018a).
* This number was indicated in CFE documentation related to the project; however, PV panels typically have an expected operational life of around 25 years under standard conditions.
** This number was indicated in CFE documentation related to the project; however, a BESS unit typically has an expected operational life of around 15 years under standard conditions.

Table 15. Installed system for each community energy project in Mexico under the FSUE program

System Information	Yoloxochio	San José de Natora	Magdaleno Aguilar
Location	Zongolica, Veracruz (18°35'56.20"N, 96°51'19.01"O)	Sahuaripa, Sonora (29°2'52.00"N, 108°45'33.00"O)	Llera, Tamaulipas (23°8'38.55"N, 98°26'29.42"O)
Number of residential PV and BESS (>300 W)	46	72	19
Number of community PV and BESS (>1,200 W)	0	4	0
Number of school PV and BESS (>900 W)	0	3	0
Number of health center PV and BESS (>1,200 W)	0	1	0
Total capacity	13.8 kW	30.3 kW	5.7 kW
Storage battery capacity	60.72 kWh	102.32 kWh	25.08 kWh

Table 16. Individual PV and battery system cost for each type of building under the FSUE program

Type of Building	Individual System Cost*	
	Mexican pesos	US Dollars
Residence	54,964.55	2,913.12
Community Center	154,929.98	8,211.29
School	55,587.00	3,200.00
Health Center	77,380.00	4,500.00

*Source: *Instituto Nacional de Ecología y Cambio Climático* 2021 & personal communication with Mariano Osvaldo Birlain Escalante, SENER, 4 March 2026.

Financing and Permitting

The projects were financed through the FSUE, with funding from the federal budget and electricity market revenues managed by the National Center for Energy Control (Centro Nacional de Control de Energía). This funding covered the procurement, installation, and commissioning of PV and BESS units for the communities as well as the electrical installation described in Table 14.

Although no specific permitting was required for the projects beyond the authorization granted to the CFE by SENER, the Mexican federal government has a regulatory framework for the FSUE actions. This framework includes:

i) constitutional and legal framework,
ii) regulations,
iii) plans and programs, and
iv) agreements, statutes, or guidelines (SENER 2018b).

Installation and Commissioning

The installation and commissioning of the PV and BESS units were managed by contractors selected through the CFE's competitive bidding process. Strict adherence to CFE's and SENER's technical guidelines ensured that all installations met standardized safety, quality, and performance benchmarks. While the system designs and specifications were fixed based on the assumptions displayed in Table 14, in many instances the contractors had to be resourceful in addressing logistical challenges, such as transporting heavy batteries and solar modules over remote, uneven terrain. In several cases, community members participated by assisting with transportation and setup, reinforcing local ownership of the project. This hands-on involvement complemented their broader role in system appropriation, which extended beyond installation to include participation in training, oversight, and ongoing use of the systems in alignment with community needs.

Operations

The contractors are bound by a 5-year performance contract with the CFE, during which they are required to address any component failures or system malfunctions. This includes repairing or replacing malfunctioning components, such as batteries or inverters, to ensure system reliability. The FSUE's framework guarantees that such performance contracts may vary by region but are tailored to cover the initial operational challenges commonly associated with new installations.

The operations phase of the projects relies on both the training provided to the community and the contractors' contractual obligations with the CFE. Following installation, contractors conduct commissioning tests to confirm that each system is functioning as intended. For more significant issues, including equipment failures or performance disruptions, contractors are required to provide solutions as part of their 5-year agreement with the CFE. This dual approach of contractor support and community capacity building underpins the sustainability of the systems and fosters long-term energy independence.

Rain or Shine: Overcoming Weather Struggles with Solar Energy in Yoloxochio - Zongolica

> “It’s a benefit for me because before, we used a lot of candles, a lot of oil lamp, and my kids […] they had to do their homework with oil lamp or battery-powered lamp, so it’s really working for me there.”
>
> Juana Hernández, community member

Yoloxochio is part of the Zongolica municipality, located in the central area of the state of Veracruz de Ignacio de la Llave, in the region called Altas Montañas (high ranges) in the Sierra Madre Oriental. The climate is warm and humid, and the land is made up of jungle, forest, and grasslands (Instituto Nacional de Estadística y Geografía 2010c). In Zongolica, more than 58 percent of the population is Indigenous; languages spoken include Nahuatl, Mixteco, Mazateco, Zapoteco, and Zoque, among others. Yoloxochio is a small community of 359 inhabitants. The community members indicated that the main economic activities in the region are agriculture—primarily coffee cultivation—and livestock farming.

Some parts of the community are accessible by the main grid, while others had no electricity prior to the FSUE. The road conditions are difficult, and community members are dispersed across rugged territory. Some members have to travel long distances by foot to reach the community’s main hub because no other type of transportation is available to them. Furthermore, outages in the areas of the community serviced by the main grid are common, due to high winds and storms, particularly in the rainy season.

Energy Transition Project Summary

The project was made possible with the joint help of the CFE, the municipal government, the Higher Technological Institute of Zongolica (Instituto Tecnológico Superior de Zongolica), and the civil organization Fund for Peace (Fondo para la Paz) (CFE n.d.). The latter played a crucial role in the development of the project, as it was involved in the selection of communities in the municipality and provided translation services (from Spanish to Náhuatl and vice versa) free of charge, for the maintenance and operation training session for community members (personal communication with Juan Pablo González of CFE, 21 June 2024). Table 17 includes a summary of the project and its impacts.

Community members that have electricity through the main grid were indirectly benefitted from the FSUE. Because the main grid experiences outages due to strong winds, the community members that have isolated PV and BESS units share their electricity with the impacted neighbors to provide basic electrical needs. As a result of the installation of these systems, a local man, Maurilio Tlehuac, started a business with his two sons to provide basic troubleshooting and maintenance for the PV and BESS units installed in the community.

As part of the broader design of the FSUE program, the Yoloxochio project incorporated a gender perspective at the planning stage, aiming to improve women's quality of life, increase their access to education, and expand their participation in community activities. The specific actions implemented included:

- Technical training for women on the handling, operation, and maintenance of solar modules.
- Workshops on gender equality and human rights, encouraging reflection on social roles and community participation.
- Educational and recreational activities for girls and boys, focused on values, responsible energy use, and a culture of peace.
- Discussion spaces to analyze the impact of electrification on women's lives, promoting their agency and autonomy.

- Bilingual delivery (Spanish–Nahuatl) to ensure cultural inclusion.
- A gender-responsive follow-up survey to assess differentiated impacts on women and men.
- Active participation of women as decision-makers throughout the electrification process.

These efforts reflect national commitments to promoting gender equity through rural electrification initiatives. Continued community engagement will be important to fully realizing the long-term benefits intended through this approach.

Key Findings

From the community's perspective, the project has fostered a strong sense of cooperation and adaptation. Residents have embraced the systems, often sharing electricity with neighbors who were not direct beneficiaries, showcasing their communal spirit. However, the mixed performance of the systems and the lack of consistent maintenance support underscores the need for improved infrastructure and training. While the project has brought significant progress, it also reveals the importance of addressing technical and operational challenges to ensure long-term sustainability and expanded access to electricity for all community members. Key insights obtained from the interview process in Yoloxochio are listed in Table 18.

Despite the challenges encountered by the Yoloxochio community, their strong cooperative spirit emerged as a vital asset, exemplified by neighbors sharing power and collaboratively addressing issues. The troubleshooting and maintenance business started by Maurilio Tlehuac and his sons could be replicated in other Mexican communities to improve capacity building. Several lessons from Yoloxochio's experience are noteworthy:

- Yoloxochio's cooperative spirit is a significant asset. Neighbors frequently share power and clear trees together, highlighting a resource that can support future projects.
- The rugged terrain and environmental conditions in Yoloxochio complicate transport, installation, and system maintenance. Heavy rain and falling branches frequently damage solar equipment, emphasizing the need for more durable systems.
- Visual guides helped residents manage and repair systems, even if they did not have literacy skills. Future projects must set clear expectations and provide better troubleshooting resources.

The following are potential next steps for Yoloxochio's continued energy transition:

- Improve transport and communication, to overcome barriers in implementation and maintenance, especially in remote areas.
- Strive to include as many households as possible, regardless of location, in future electrification initiatives, to reduce frustration and boost engagement.
- Simplify and expedite government processes, to reduce delays in delivering approved resources and benefits to the community.

Table 17. Yoloxochio - Zongolica project summary

Project details	Description
Installed capacity	13.8 kW (see Table 15 for details)
Timeline	December 2020–April 2021
Total cost	P$2,047,011 (US$102,335)
Funding sources	Mexican federal government
Project lead and key partners	Fondo para la Paz, SENER, CFE
Ownership	Individual ownership
Project impacts	• Small businesses like carpentry shops and stores were able to expand services and boost productivity through reliable electricity. A local family has emerged as trusted experts in PV system repairs, creating a niche economic opportunity. • The project has strengthened communal bonds as households share solar electricity for daily needs like charging phones and powering appliances, fostering resilience and interdependence. Collaborative efforts, such as organizing group cleanups to address shading issues, highlight the community's collective problem-solving and commitment to maintaining energy access. • By choosing PV and BESS as an energy source instead of kerosene for lighting, the community avoids the release of 15.04 tonnes of carbon dioxide equivalent (CO_2e) annually (personal communication with José Vicente Hernández of CFE, 2 April 2024). • Improved household lighting has enhanced safety for women; some community members, including one resident interviewed, noted feeling more secure at night with reliable electricity.

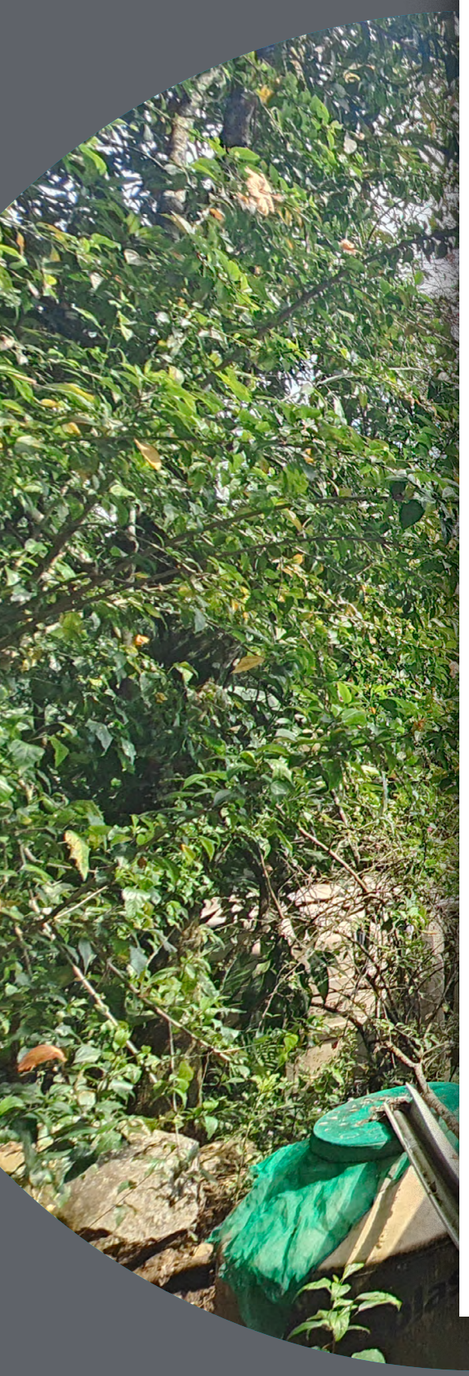


Table 18. Yoloxochio - Zongolica interview findings, by project development phase

Project Development Phase	Key Findings
Planning	• This phase involved significant coordination between the community, Fondo Para la Paz, and CFE. The local leadership worked to ensure that required documentation for project approval was submitted to the central offices in Mexico City. • Fondo para la Paz played a crucial role in the development by acquiring funding and providing translation services free of charge for the maintenance and operation training of community members (personal communication with Juan Pablo González of CFE, 21 June 2024. • The delay in project authorization was a common challenge, with federal-level processes taking considerable time.
Technology selection and procurement	• Due to geographic conditions and the dispersion of housing at the time of project approval, extending the electricity grid to these communities was not feasible; therefore, solar PV with BESS were installed. • In addition, see Planning, Technology Selection, and Procurement, under Section 4.2.
Financing and permitting	• No project-specific findings, as the financing and permitting phases are consistent for all projects in Mexico (refer to Section 4.2).
Installation and commissioning	• The installation phase was supported by community members who coordinated with technicians, although direct assistance during the installation process was not explicitly mentioned. • Once installed, the systems were tested for proper operation. Training sessions were held, though some attendees reported gaps in the coverage of essential maintenance practices. Practical demonstrations helped community members understand system functionality. • Manuals detailing the appropriate use of the systems were provided to the majority of the residents; however, distribution was not comprehensive, and maintenance instructions were not consistently shared across all households.
Operations	• System performance has been mixed, with reports of frequent outages and broken components due to overloading. Tree shading and seasonal challenges such as reduced efficiency during the rainy season were noted as significant operational hurdles. • Community members have suggested increasing system capacity to support larger appliances and improving maintenance services for long-term reliability and meeting future needs. • Despite challenges, the community has embraced the systems, often sharing electricity with neighbors who were not yet beneficiaries. This cooperative approach reflects Yoloxochio's strong communal ties and highlights the need for expanded electrification efforts.

Bridging Distances: Energy Resilience in San José de Natora

> “In the middle school there was no type of lighting; now, it makes working easier for me, with the energy, because I have a computer, a printer, water cooler, fans for the hot season. And here at my home it’s the same, the Internet, washing machine, fridge, lighting—and, well, it feels good to have this type of convenience.”
>
> Yadira Urquijo Rivas, community member and school teacher

San José de Natora is located in the Sahuaripa municipality of the northwestern state of Sonora, a primarily desert state, with semi-dry and semi-warm climate. The area is characterized by boulders, rivers, and the impressive landscapes of the Sierra Madre Occidental mountain range. The vegetation is predominantly forest, with grasslands, mesquite trees, and desert shrubs (Instituto Nacional de Estadística y Geografía 2010b). The total population of Sahuaripa was 5,245 inhabitants in 2020, a decrease of 13 percent compared to 2010 (Secretaría de Economía 2020). The language of a small part of the community is Indigenous. The municipality’s economy is largely driven by agriculture— including livestock production— which represents 1.25 percent of the territory, and mining. Saddles and all necessary livestock tools are manufactured in the municipality as well (Instituto Nacional de Estadística y Geografía 2010b).

San José de Natora is located 213 km east of the state capital of Hermosillo, closer to the border of neighboring state Chihuahua than to the state capital. There is no direct paved road linking San José de Natora to the Sahuaripa county seat; to reach it, eight hours of car travel over dirt road and rough terrain is required. Natora’s closest neighbors are Guadalupe el Grande, 10 km to the south, and Tunapa, about 15 km to the north. There are no paved roads connecting them, and only some of the community members own vehicles. Due to its remoteness (90 km from the main grid) and small population (288 inhabitants), electrification had not reached the community before the FSUE was implemented.

Energy Transition Project Summary

San José de Natora was the largest of the Mexican communities whose project was selected for this study. The community has 72 houses with 300 W systems installed, three schools with 900 W systems, and one clinic and four community meeting centers with 1,200 W systems. The implementation of PV and BESS has improved local energy reliability, supported small businesses and essential services, and benefited the entire community. Table 19 gives a summary of the project and its impacts.

Key Findings

The successful implementation of solar energy in the community was rooted in collaborative planning and strong local leadership. Key insights from the interview process at San José de Natora are listed in Table 20.

Existing systems meet basic energy needs for homes, schools, and community centers. Although maintenance can prove difficult for the community, members emphasize that their quality of life has been greatly improved by the implementation of this project. The following are lessons learned from San José de Natora's energy project:

- Municipal collaboration significantly accelerates project implementation; without it, progress would take much longer. The Comisariado Ejidal played a pivotal role by organizing residents and streamlining administrative processes while municipal representatives provided critical logistical support, such as document preparation and submission.
- Current PV and BESS installations only address basic needs for homes, schools, and community centers and fall short for businesses and broader community requirements, highlighting the need for a more robust solution.
- Clear rules on ownership and usage are crucial, to prevent issues such as residents withholding access to shared electricity.
- Maintenance challenges persist, due to unclear communication channels, causing delays in the reporting of issues, even though CFE responds swiftly when notified.

The following are potential next steps for the San José de Natora community:

- Seek funding for future maintenance needs, as FSUE-funded projects will require ongoing support despite communities being classified as electrified.
- Scale infrastructure to meet growing demand by initiating support programs that allow residents to acquire appliances like refrigerators, fans, or washing machines, now that stable electricity is available.
- Train and designate a local technician to handle maintenance and repairs, ensuring he/she has the knowledge and tools to manage equipment and communicate with CFE when external assistance is required.
- Provide spare parts and resources locally, to reduce reliance on external support and minimize transportation delays caused by the community's isolation.
- Offer training and resources for residents, enabling the growth of small businesses that could leverage electricity for refrigeration, Wi-Fi systems, or other technologies to drive economic development.

Table 19. San José de Natora project summary

Project details	Description
Installed capacity	30.3 kW (see Table 15 for details)
Timeline	June–December 2021
Total cost	P$4,082,983 (US$204,149)
Funding sources	Mexican federal government
Project lead and key partners	SENER, CFE, local and municipal authorities
Ownership	Individual ownership
Project impacts	• By providing consistent electricity, the project has eliminated the need for alternative, often costly methods for lighting, refrigeration, and daily household operations, freeing up income for other uses. Community members expressed satisfaction with the clean energy provided by the system, which has also sparked interest in renewable energy and sustainability practices. The use of PV and BESS prevents the release of 26.16 tonnes of CO2e annually compared to kerosene lighting (personal communication with José Vicente Hernández of CFE, 2 April 2024). • Reliable electricity has significantly improved quality of life, enabling families to store insulin safely in refrigerators—a critical advancement for diabetes management—replacing labor-intensive ice-bucket methods. Access to appliances like fans, blenders, and washing machines has eased daily chores, enhanced comfort during extreme weather, and extended productive and social activities into the evenings. These changes foster health, convenience, and stronger community bonds.

Table 20. San José de Natora interview findings, by project development phase

Project Development Phase	Key Findings
Planning	• The Comisariado Ejidal (elected body that represents communal landholders, or ejidatarios) played a key role by organizing the community and facilitating the submission of necessary documentation for the project. • Representatives from the municipality, including the contraloría, or comptroller, provided logistical assistance such as printing, organizing, and submitting documents required for eligibility. • Local leadership and residents met to outline project objectives and secure agreement on participation. Local leaders guided residents through the administrative requirements, ensuring clarity of the process and building trust in the project.
Technology selection and procurement	• No project-specific findings, as the technology selection and procurement are consistent for all projects in Mexico (refer to Section 4.2).
Financing and permitting	• No project-specific findings, as the financing and permitting phases are consistent for all projects in Mexico (refer to Section 4.2).
Installation and commissioning	• Transporting equipment to the remote location was challenging due to the lack of road infrastructure.
Operations	• The operations phase relies heavily on the training provided to residents during installation. This training empowered community members to handle routine maintenance tasks independently, including cleaning solar panels to maintain efficiency and monitoring battery status and optimal energy usage to ensure system performance. • Battery replacement is expected after five years, coinciding with the expiration of the contractor's service agreement. Some batteries have already been replaced. • While systems are generally reliable, occasional outages or disruptions have been reported. These incidents often result from varying maintenance practices or normal component wear. • Residents report system issues to CFE, but the process has been inconsistent. Additionally, a community member was given extra energy to power public lighting; however, the lack of clear operation rules resulted in the community member withholding access to shared electricity.

Lighting the Way: Energy Access and Cooperation in Magdaleno Aguilar

> “We are very happy because I have my blender, I have my fridge, and the meat doesn’t spoil anymore, the cheese doesn’t spoil anymore. And before, I had to have my insulin on ice, so I don’t struggle anymore. And we are very grateful.”
>
> Rosa Fonseca Piñón, community member

Magdaleno Aguilar is a very small community of 76 inhabitants, located in the foothills of the Sierra Madre Oriental and Sierra Tamaulipas Mountain ranges, in the Llera municipality of the northeastern state of Tamaulipas. The terrain varies in elevation and climate and features vegetation that ranges from tall, thorny shrublands on the mountain foothills to lower shrublands and deciduous, thorny, low forests in the central region (Instituto Nacional de Estadística y Geografía 2010a). The economy primarily relies on crop cultivation, which occupies 33 percent of the territory, and on livestock production and apiculture on a smaller scale. Women in the region produce clay pots and cast-iron grills, and craft tablecloths and woollen fabrics, shawls and yarn. Other activities include the fabrication of wood chairs and couches and palm brooms (Instituto Nacional de Estadística y Geografía 2010a).

The road to Magdaleno Aguilar is rough, and the community is 12 km from the main grid. Like the other communities consulted for this document, Magdaleno Aguilar had no access to electricity prior to the implementation of the FSUE, because of its remote setting and small population.

Energy Transition Project Summary

The entire community of 76 inhabitants benefitted from the FSUE through the installation of PV and BESS in 19 residential buildings. Initially, some community members hesitated to submit their paperwork to apply for the FSUE but were encouraged after seeing how access to electricity helped their neighbors. A community center is expected to be electrified through the FSUE as well. The project also motivated the neighboring community of Nuevo Progreso to apply for the program, and the two communities have coordinated closely on project-related matters, sharing lessons learned and supporting each other in implementation. Table 21 gives a summary of the project and its impact on the community.

Key Findings

The solar energy initiative in Magdaleno Aguilar was driven by robust local leadership and community coordination, with ejido representatives and a former delegate spearheading the petition for PV and BESS and navigating administrative processes. Key insights from the interview process with the Magdaleno Aguilar community are listed in Table 22.

The project showcased how targeted energy interventions can profoundly enhance quality of life in remote areas, balancing practicality with transformative impact. The following takeaways from the consultation process stand out as essential lessons:

- Early hesitation among residents highlighted the importance of robust initial engagement to explain the project's benefits and build trust. Witnessing neighbors' positive experiences proved to be a powerful motivator for broader participation.
- Difficult access to Magdaleno Aguilar due to rugged terrain and limited travel infrastructure emphasized the need for careful planning and allocation of resources for transportation and equipment delivery.

- Standardized PV and BESS units ensured a consistent and manageable implementation process, but their capacity limitations underline the need to design systems that align more closely with community needs.
- Frequent nighttime outages suggest that a better understanding of local energy usage patterns is needed at the planning stage, particularly in communities with limited capacity for storage and generation.
- The community's reliance on external maintenance for PV and BESS units, and their lack of local repair expertise underscore the need for long-term support mechanisms, such as training programs, to build local technical capacity. At the same time, residents expressed distrust for CFE and frustration with long wait times for support. The community would greatly benefit from having the tools and knowledge to troubleshoot their systems independently.

The following are potential next steps for Magdaleno Aguilar's continued energy transition:

- Expand training programs, to develop local technical expertise for PV and BESS maintenance and provide the community with troubleshooting tools to reduce dependency on external support.
- Conduct detailed studies on community energy usage, to inform the design of future energy, including optimized storage and generation capacity.
- Explore the potential for phased system upgrades, to accommodate increasing energy demands over time.

Table 21. Magdaleno Aguilar project summary

Project Details	Description
Installed capacity	5.7 kW (see Table 15 for details)
Timeline	July–November 2021
Total cost	P$847,671 (US$42,383)
Funding sources	Mexican federal government
Project lead and key partners	SENER, CFE
Ownership	Individual ownership
Project impacts	• While no direct income was generated, households experienced greater financial stability by spending less on conventional lighting and losing less food to spoilage. Fewer market trips also cut costs, freeing up resources for other needs. These savings highlight the project's role in indirectly strengthening economic resilience. • The transition to solar PV systems for electric lighting instead of kerosene lighting prevents the release of 6.21 tonnes of CO2e annually (personal communication with José Vicente Hernández of CFE, 2 April 2024). This initiative supports Mexico's environmental goals while providing a model for clean energy adoption in remote communities. • The introduction of PV systems has transformed daily life by enabling reliable food preservation (e.g., dairy, meats, vegetables) and refrigeration of lifesaving insulin for diabetes management, reducing stress and enhancing health outcomes. Initial skepticism among residents faded as tangible benefits became evident, leading to broader community participation. Improved lighting, cooling, and productivity have also increased safety, comfort, and communal pride.

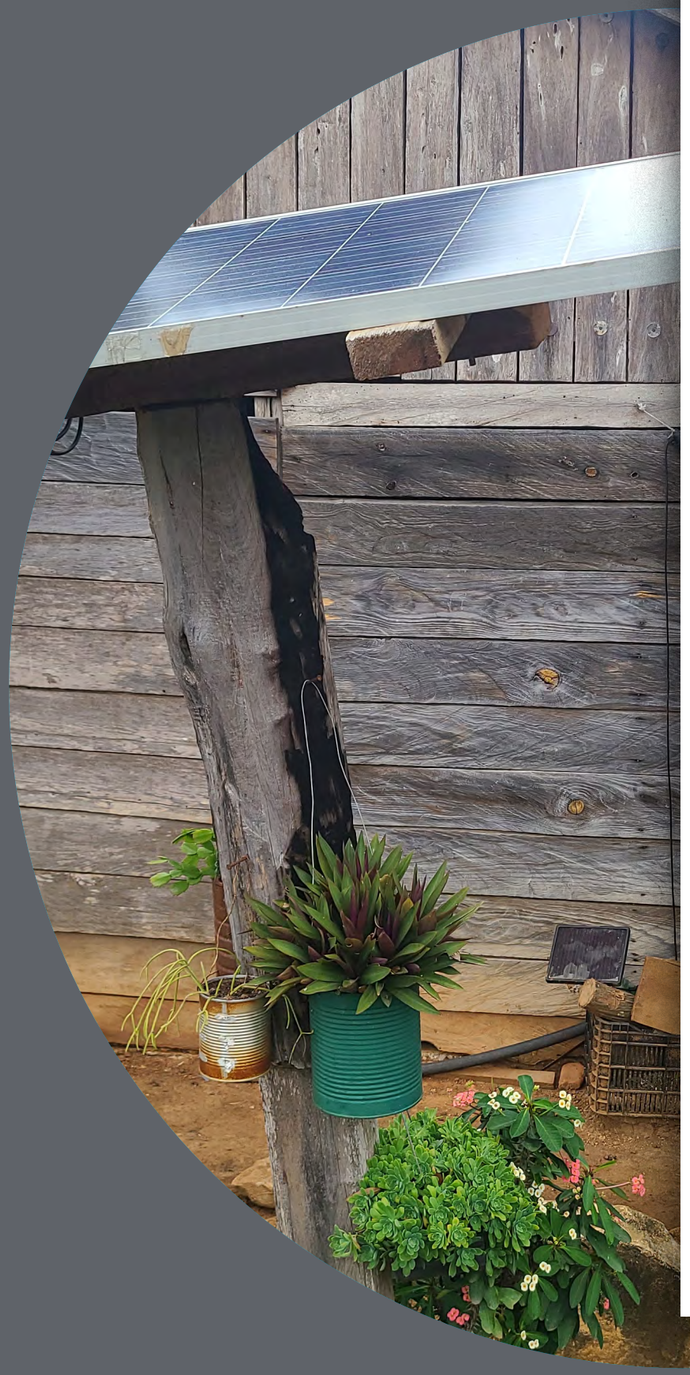


Table 22. Magdaleno Aguilar interview findings, by project development phase

Project Development Phase	Key Findings
Planning	• A community member highlighted that the former municipal delegate played a critical role in organizing the petition for PV and BESS, demonstrating strong internal coordination. Similarly to other FSUE-supported projects, the submission of required documentation was facilitated by local leadership. • Community members emphasized the year-long wait between application submission and the project's approval, reflecting the logistical challenges specific to planning projects in remote areas like Magdaleno Aguilar. • Reaching Magdaleno Aguilar required navigating rugged terrain using 4x4 vehicles, adding complexity to the planning and implementation phases. These unique access constraints made early-stage coordination and scheduling particularly critical.
Technology selection and procurement	• No project-specific findings, as the technology selection and procurement are consistent for all projects in Mexico (refer to Section 4.2).
Financing and permitting	• No project-specific findings, as the financing and permitting phases are consistent for all projects in Mexico (refer to Section 4.2).
Installation and commissioning	• The community reported a smooth installation process despite the logistical challenges posed by the terrain. The systems were installed over a span of two months. • Residents participated in the installation phase, observing the setup process and asking questions about system operation. This engagement helped build confidence in using the technology.
Operations	• Community members noted no significant issues during the initial operational period. • Community members expressed profound gratitude for the PV and BESS, highlighting the transformative impact of the systems on daily life by powering essential appliances like refrigerators and lighting. However, they also noted frequent outages during the night due to capacity limitations. Despite using minimal electricity, the systems often fail to meet even basic needs. • Residents voiced concerns about battery lifespan, noting that while current batteries were performing well, replacements might be needed within a few years. The community relies on the CFE's warranty and service agreements to address future maintenance needs. • Magdaleno Aguilar has not yet developed a local workforce for PV and BESS maintenance, unlike some other FSUE communities where residents have been trained as local technicians. However, the community remains proactive in seeking external support for maintenance when required.

5. Common Themes in Renewable Energy Transitions of Remote and Indigenous Communities Across North America

The remote and Indigenous communities selected for these case studies are navigating renewable energy transitions shaped by unique cultural, geographic, and socioeconomic contexts. Although each community's experience differs, clear patterns and shared lessons emerge when analyzing their collective journeys. By mapping these experiences onto a progression summary—from basic renewable electrification to fully integrated renewable microgrids (as illustrated in Figure 3)—we can better understand distinct phases and the thematic insights arising at different transition scales. However, it is important to note that communities do not necessarily move sequentially through every scale; some may initiate their transition directly at more advanced levels, depending on their specific contexts and resources. Table 23 complements this visual progression, summarizing community examples, core characteristics, and opportunities associated with each scale. Collectively, these resources highlight common themes and provide a structured understanding critical to supporting equitable and sustainable energy transitions.

Technology Maturity: Balancing Innovation and Reliability

Communities emphasize selecting renewable energy technologies that match their operational capacity and long-term maintenance needs. Early renewable integration efforts, such as in Shungnak and Kobuk, favored reliable, proven systems that complemented existing diesel infrastructure. More complex projects—like Kwanlin Dün First Nation's wind and Inukjuak's hydroelectric systems—required greater technical skills and resource planning. As Borrego Springs shows, advanced systems can encounter operational issues if local support capacity is limited. Technology choices must balance maturity, resource adequacy, maintenance needs, and available expertise to ensure sustainable outcomes.

Community Planning and Self-determination

The degree of active community engagement and self-determination significantly evolves throughout the stages of energy transition depicted in Figure 3. Initially, engagement may focus primarily on identifying and addressing essential energy access needs. However, as communities progress toward more-integrated or more-centralized renewable systems—such as those demonstrated by Toro Negro and

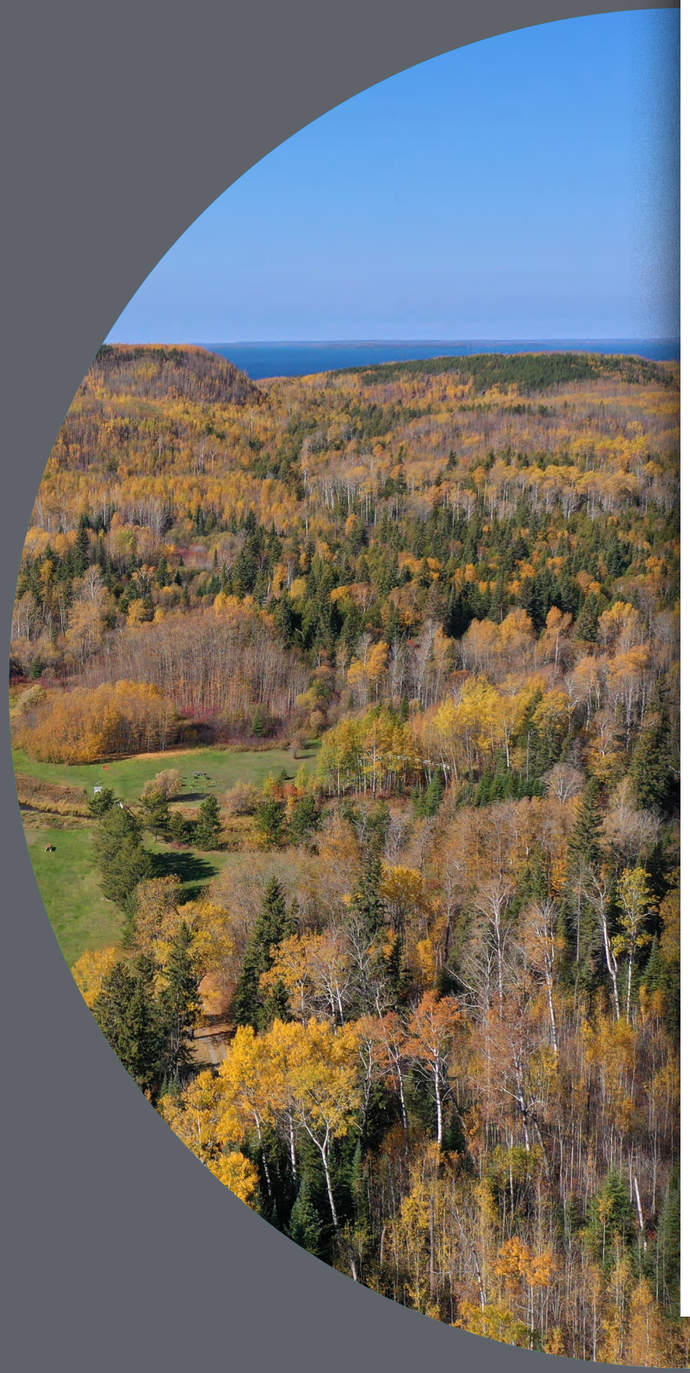
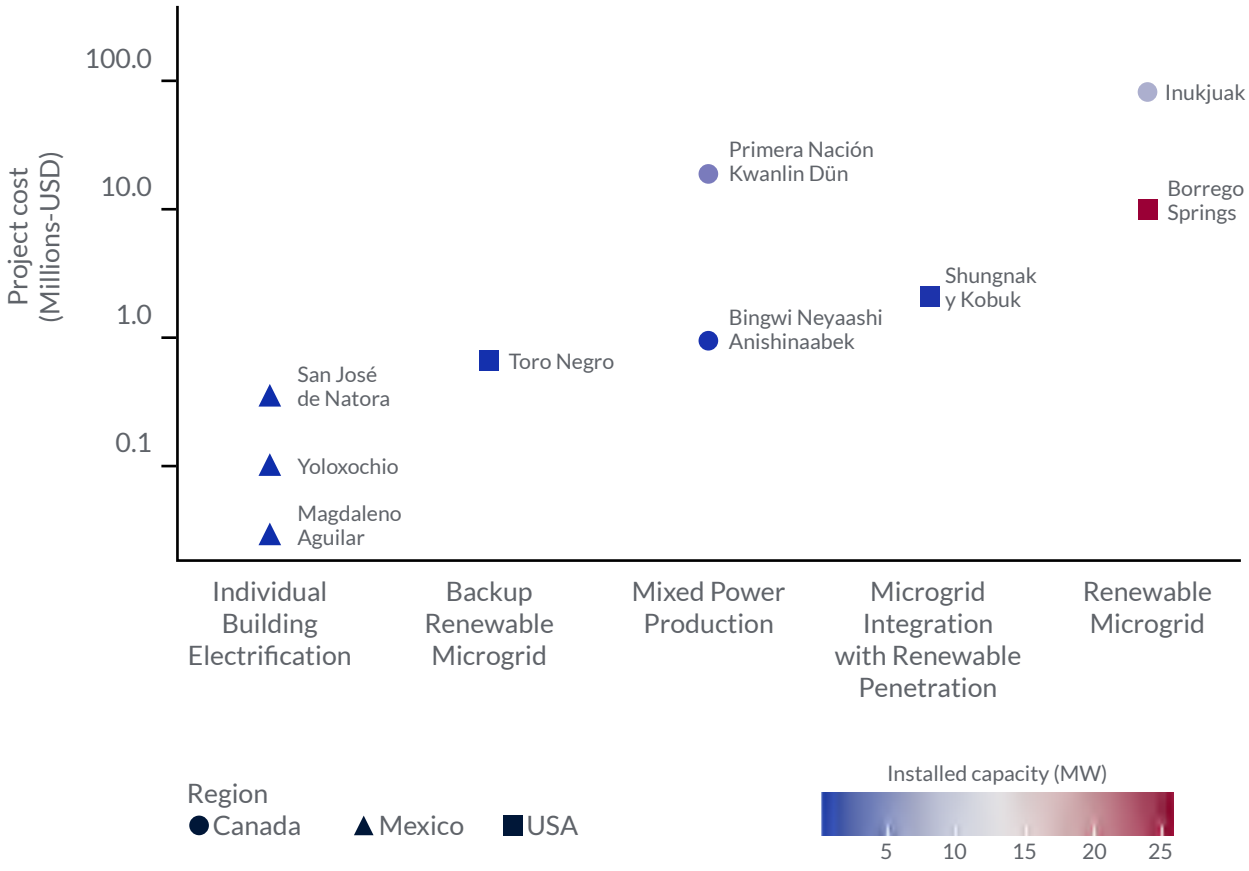


Table 23. Typology of renewable energy system scales, across case study communities

Scale	Community Examples	Key Characteristics	Main Challenges	Impacts
Basic electrification	San José de Natora, Yoloxochio, Magdaleno Aguilar (PV and BESS)	Individual renewable systems, small budgets, direct benefits	Basic logistics, limited local technical capacity	Immediate improvements in health, education, and communication
Connected individual units (backup renewable microgrid)	Toro Negro (PV and BESS)	Distributed renewable/storage assets, potential grid-connection	System integration, effective management of storage and operations and maintenance	Enhanced reliability, community-level energy resilience
Mixed power production	Bingwi Neyaashi Anishinaabek (biomass), Kwanlin Dün First Nation (wind)	Centralized renewable assets, diverse energy sources	Technical complexity, specialized expertise needed	Broader economic benefits, initial revenue generation
Microgrid integration with renewable penetration	Shungnak and Kobuk (microgrid)	Renewable microgrid, integrating multiple energy sources	Regulatory complexities, advanced system management	Regional energy collaboration, risk distribution
Renewable microgrid	Borrego Springs (microgrid), Inukjuak (hydroelectric)	Fully resilient renewable microgrid, redundancy and diversification	High initial capital, long-term technical management	Sustained energy sovereignty, economic returns, enhanced regional resilience

Bingwi Neyaashi Anishinaabek—community members take increasingly active roles through ongoing consultation, decision making, cultural alignment, and local governance. Robust community engagement, initiated from the earliest assessment phases and sustained through every project development stage, fosters local ownership and broad-based support. This inclusive engagement and leadership approach is crucial in driving communities toward achieving enduring sustainability, resilience, and energy sovereignty.

Figure 3. Renewable energy project typologies, by cost and installed capacity, across case study communities



Budget Efficiency and Community Impact

The impact of renewable energy projects does not necessarily correlate directly with budget size. Early-stage electrification projects, despite their relatively smaller budgets, often generate immediate, transformative benefits, significantly enhancing quality of life through improved health, education, and basic communication (examples from Table 23 include San José de Natora, Yoloxochio, and Magdaleno Aguilar). In contrast, advanced microgrid systems like in Borrego Springs and Inukjuak, though substantially more expensive, deliver broader socioeconomic benefits, including sustained economic activity, long-term energy reliability, resilience, and revenue generation opportunities. Each stage thus offers distinctive, complementary impacts, underscoring the need to align strategic investment with community-specific transition objectives.

Partnerships and Consensus Building

Successful renewable transitions depend critically on effective partnerships between communities, technical providers, utilities, and governmental entities. As illustrated in Table 23, communities transitioning into more-advanced stages—such as mixed-generation and renewable microgrids—face increasing partnership complexity. For example, regulatory and governance frameworks are especially critical in networked microgrids like in Shungnak and Kobuk, where coordinated resource sharing demands robust partnerships. Effective partnerships enhance both community trust and project sustainability, ensuring alignment across stakeholder priorities.

Technical Expertise and Community Capacity Building

Technical expertise alone is insufficient; successful projects integrate technical capabilities with deliberate capacity building tailored to community needs and priorities. As illustrated in Table 23, smaller-scale projects benefit from straightforward, community-focused training programs aimed at essential maintenance skills. In contrast, larger-scale initiatives—such as those led by Kwanlin Dün First Nation and Borrego Springs—require advanced technical knowledge combined with deliberate strategies to boost local employment, skills transfer, and community-led management. Successful capacity building begins at the earliest planning stages, actively engaging diverse community members—including youth, women, and marginalized populations—to build lasting local competencies, empower

communities, and support long-term operational sustainability. This inclusive approach ensures that as communities pursue increasingly sophisticated energy systems, technical progress aligns closely with social equity and self-determination goals.

Energy Storage as Foundational

Energy storage consistently emerges as foundational to successful renewable transitions. Even with modest storage capacities, early electrification projects (e.g., San José de Natora and Yoloxochio) have significant benefits, such as immediate reliability improvement and reduced diesel dependence. However, as communities evolve to intermediate and large-scale projects (e.g., Toro Negro and Shungnak and Kobuk), expanded storage capacity becomes integral to achieving deeper resilience, addressing renewable intermittency, and ensuring stable, consistent energy supply. Properly integrated storage solutions thus underpin long-term success across all levels.

Long-term Operations and Maintenance

Sustainable renewable transitions require consistent, well-funded, long-term operations and maintenance (O&M) frameworks. The energy transition levels on the x-axis of Figure 3 incur increasing O&M complexity and importance from left to right, as communities progress from more basic to larger scales. Basic electrification often presents logistical and technical challenges for O&M, particularly in remote areas. In the case of the Mexican communities, current maintenance is primarily supported through medium-term contracts. However, the federal government is actively working to shift toward community-based O&M models, aiming to strengthen local capacity and support long-term sustainability. Communities at advanced energy transition levels, like Borrego Springs and Inukjuak, demonstrate established O&M frameworks, institutional support structures, and local technical expertise, all critical to ensuring the long-term operational success and sustainability of their renewable microgrids.

Public Investment and Financial Structuring

Public investment remains a critical catalyst for successful energy transitions, regardless of scale, as it reduces financial risk that would otherwise fall on communities or deter private-sector engagement and enables infrastructure development. Small-scale electrification predominantly benefits from initial public investment to establish foundational energy access, whereas large-scale projects such as mixed-generation and renewable microgrids leverage public funds strategically to attract private investments, develop critical infrastructure, and support more-complex solutions. Communities progressing through the different levels presented in Table 23 thus benefit from tailored financial structuring aligned with their evolving needs.

Revenue Generation and Financial Sustainability

As communities advance through renewable energy penetration levels, the ability to generate revenue increasingly becomes a central element of sustainability. Advanced microgrid systems such as those in Inukjuak and Borrego Springs demonstrate opportunities to become IPPs, reinvesting revenue into local infrastructure, workforce development, and long-term O&M financing. Establishing revenue streams strengthens local economies, enabling sustained community resilience and autonomy beyond initial project funding.

The diverse renewable energy transitions of remote and Indigenous communities across North America reveal consistent thematic priorities and strategic insights essential to achieving long-term success. While these shared experiences provide a framework for guiding future energy transitions, additional quantitative analysis and ongoing data collection remain critical. Further research building on the findings and structure presented here will enable more-precise benchmarking, targeted interventions, and informed policymaking. Ultimately, understanding each community's current scale within the transition framework clearly reveals remaining challenges and areas for strategic investment, facilitating equitable progress toward lasting resilience, economic sustainability, and energy sovereignty.

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Annex: Policies Enabling Rural Electrification Projects

This annex presents examples of national and federal policies that directly influence the development and implementation of rural and remote community electrification projects across Canada, Mexico, and the United States. These policies establish the legal, financial, and programmatic frameworks that enable or support the case study projects described in this report.

Canada

Clean Energy for Rural and Remote Communities

The Clean Energy for Rural and Remote Communities (CERRC) program is a central enabler of renewable energy transitions in Canada's off-grid regions. Administered by Natural Resources Canada, CERRC provides funding for projects that reduce reliance on diesel in Indigenous, rural, and remote communities by supporting renewable energy deployment, capacity building, and community energy planning (Natural Resources Canada 2025). The program was directly relevant to the projects featured in this report, including those in Inukjuak and Kwanlin Dün First Nation, by providing funding mechanisms and technical assistance tailored to Indigenous-led initiatives. It aligns with Canada's commitments to reconciliation and clean growth.

Indigenous Off-Diesel Initiative

The Indigenous Off-Diesel Initiative (IODI), also managed by Natural Resources Canada in partnership with the Indigenous Clean Energy Social Enterprise, supports community energy champions to lead projects that reduce diesel use through renewables (Government of Canada 2023). IODI played a role in capacity development and leadership training in communities like those described in the report. It complements broader policy efforts by funding energy plans and initial project stages in Indigenous communities.

Northern REACHE Program

The Northern Responsible Energy Approach for Community Heat and Electricity (Northern REACHE) program supports renewable energy and energy efficiency projects in the territories (Crown-Indigenous Relations and Northern Affairs Canada

2023). It is led by Crown-Indigenous Relations and Northern Affairs Canada and was developed in response to the challenges posed by remote northern infrastructure. REACHE supports planning and deployment of clean energy and heat systems in Yukon and the Northwest Territories, and it enabled preliminary planning and feasibility work relevant to the projects discussed, particularly in Kwanlin Dün First Nation.

Pan-Canadian Framework on Clean Growth and Climate Change

The Pan-Canadian Framework on Clean Growth and Climate Change provides the overarching national policy context within which all of the above programs operate (Environment and Climate Change Canada 2016). Endorsed in 2016, it sets the foundation for Canada's net-zero goals and directs federal investment toward reducing emissions and supporting clean technology. It explicitly calls for clean energy development in Indigenous and remote communities, establishing a political and fiscal mandate for programs like CERRC and REACHE.

United States

Rural Electrification Act of 1936

The Rural Electrification Act (REA) of 1936 remains the cornerstone of rural energy development in the United States. Initially enacted to extend electricity to rural areas through low-interest loans, the REA authorized federal assistance to cooperatives and public utilities. Today, the US Department of Agriculture's (USDA's) Rural Utilities Service administers the program, offering loans and loan guarantees for energy infrastructure in underserved communities. This legal and institutional framework continues to provide the foundational support for projects in regions like the Northwest Arctic Borough.

USDA Rural Energy Programs

The USDA's Rural Development Electric Programs fund construction, modernization, and improvement of electric distribution infrastructure in rural areas (USDA Rural Development n.d.). Through programs like the High Energy Cost Grant and the Electric Infrastructure Loan Program, these initiatives reduce the financial burden for rural communities seeking to diversify or stabilize their energy supply. The Northwest Arctic Borough's microgrid efforts benefited from this structure.

Federal Energy Regulatory Commission Order No. 841

Issued in 2018, Federal Energy Regulatory Commission (FERC) Order No. 841 directed regional transmission organizations and independent-system operators to ensure that energy storage resources could participate in wholesale energy markets (FERC 2020a). While its primary impact is on grid-connected areas, the order established a regulatory precedent for valuing storage assets in energy planning. This helped validate the use of battery storage in resilience-focused microgrids such as those in Borrego Springs and Alaska.

Federal Energy Regulatory Commission Order No. 2222

FERC Order No. 2222, released in 2020, facilitates the aggregation of distributed energy resources, including rooftop solar and battery systems, for participation in regional markets (FERC 2020b). Although more impactful in grid-connected regions, the order aligns with broader federal policy trends supporting decentralized energy development and flexibility—principles critical to remote community energy strategies.

Mexico

2013 Energy Reform (Reforma Energética)

The 2013 Energy Reform introduced constitutional changes that restructured Mexico's energy sector, allowing for private investment and promoting universal electricity access. This reform created the foundation for the FSUE by enabling a legal and institutional framework that supports government-led electrification efforts in rural and marginalized communities.

Published in 2014 as a product of the Energy Reform, the Electricity Industry Law establishes the legal basis for the FSUE (Secretaría de Goberanción 2014). Article 126 specifically mandates the creation of a universal electricity service fund to serve remote and underserved communities. It defines the roles of SENER and CFE in planning and executing electrification projects.

2025 Energy Reform

On 18 March 2025, the Diario Oficial de la Federación published a package of eight secondary laws that restructure various components of Mexico's energy sector. Among the key instruments are the Law of the State-owned Public Company, Federal Electricity Commission (CFE); the Electricity Sector Law; and the Energy Planning and Transition Law. The new legal framework establishes CFE as a state-owned public company with its own legal personality and assets, sectorized under SENER. It assigns CFE expanded responsibilities in electricity generation, transmission,

distribution, and basic supply, as well as the provision of internet and telecommunications services, in support of broader access and social equity objectives.

The Electricity Sector Law replaces the 2014 Electricity Industry Law and introduces a state-preference model for electricity generation, reserving at least 54 percent of generation for CFE. It maintains specific modalities for participation by third parties through distributed generation, self-consumption, and isolated systems. Systems under 0.7 MW are exempt from requiring permits, and projects up to 20 MW may follow simplified procedures. The Energy Planning and Transition Law creates a new framework for national energy planning, mandating the development of 15-year planning instruments that incorporate considerations such as energy justice, sustainability, human rights, and regional development.

In addition to institutional reforms, the legal package dissolves the Energy Regulatory Commission and the National Hydrocarbons Commission, consolidating their functions within a newly established National Energy Commission. This new body is responsible for regulatory oversight across the electricity and hydrocarbons sectors and operates under the coordination of SENER. These changes form part of a broader reorganization aimed at centralizing energy sector governance and aligning operational mandates with social policy goals.

FSUE Operational Rules

SENER published official operational rules for the FSUE that outline its implementation mechanisms (SENER n.d.). These rules define eligibility criteria, project prioritization (based on social and economic impact), and performance obligations for contractors. The rules also explain how the FSUE is financed: primarily through federal budget allocations and electricity market revenues.