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Can renewable energy work for rural societies? Exploring productive use, institutions, support systems, and trust for solar electricity in the Navajo Nation

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ABSTRACT

Reliable electricity and water access remain major challenges in rural communities worldwide. Standalone renewable energy systems show promise in improving access, but successful long-term outcomes remain infrequent in practice. To achieve sustainable outcomes, planners and decision makers should place a greater emphasis on understanding community context to determine the technological and social appropriacy of renewable energy technology. This article investigates a case study of renewable energy systems in the Navajo Nation to develop an understanding of what technical and social considerations may be necessary. A qualitative exploratory data analysis approach is used to perform a comparative analysis of two programs that deployed solar home systems (SHS) and atmospheric water generation (AWG) systems to address electricity and water needs in the Nation, respectively. The findings reveal that renewable energy programs should critically evaluate four factors related to technological and procedural appropriacy. These four factors are (1) an understanding of the productive use of the technology in context, (2) the need to operate within extant institutional paradigms, (3) the capacity to develop and maintain a support network, and (4) the need for trust building. The findings indicate that productive use of renewable energy is determined by end-user application and its usefulness in the community's rank order of priorities. It also demonstrates that social acceptance of renewable energy is affected by the willingness of programs to conform to existing institutional paradigms. This article refines and expands upon existing themes of social acceptance, making them more application oriented by focusing on the planning phase.

1. Introduction

Despite the progress made worldwide over the last century towards development of public utility infrastructure systems, an estimated 759 million people lack access to reliable electricity [1], and an estimated 800 million people have difficulty obtaining safe drinking water [2]. Communities in rural, remote, and underdeveloped regions of the world are disproportionately affected. In 2020, 3% of the global urban population and 17% for the global rural population were without electricity [1]. Similarly, eight out of ten people without basic drinking water services were estimated to live in rural areas as of 2020 [2]. This dearth of basic access to reliable electricity and safe drinking water has major impacts on various quality of life metrics, including life expectancy, child mortality, mean years of schooling, and income, among others [3–6].

The development of public infrastructure to deliver utility services to rural communities lags behind that of their urban counterparts. In large part, this is because such development is difficult to justify based on the very high costs associated with *last mile connectivity*. As a result, communities that live beyond the edge of the public utility infrastructure network have historically been unable to reliably, safely, and cost-effectively access these services. Decentralized technological solutions present a great benefit in such scenarios as they can bypass the *last mile connectivity* cost barrier. The ability of these solutions to function independently of any larger utility networks, as well as their modular deployment capability, means they offer a significant value proposition toward improving the general quality of life in remote and rural communities [7]. As the production costs for technology components such as batteries, photovoltaic (PV) panels, and power electronic converters continue to drop, their transformative potential is only likely to increase [8].

However, while these technologies show considerable promise in theory, the on-the-ground reality of these deployed systems has been

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less than satisfactory [7,9,10]. Follow-up investigations of technological solutions deployed in rural and remote communities have often found them to be only partially functional, in serious disrepair, or completely abandoned [9,10]. Accurate numbers are sparse in literature, but anecdotal evidence presented by Corsair suggests that 80%–90% of rural solar photovoltaic (PV) systems can be non-functional well before the end of their design life [9]. Feron cites some documentation studies for off-grid PV energy systems in Guatemala and Laos, which found 45% and 65% of systems were non-functional, respectively [7]. Investigations into success and failures increasingly find that purely technical issues are generally not the primary cause of failure or abandonment [10–12]. Even when deployed systems work in ways for which they were technically designed, users in the communities may still consider them unsuccessful or inappropriate for meeting local needs [7,13]. Collectively, these findings suggest that the social dimension of a technological solution can rival the technical design in relevance, as an incomplete understanding of people and society may create dissonances in expectations and disparities in design that ultimately affect performance and outcome [14,15]. A key principle of the emerging discipline of *Contextual Engineering* [16] asserts that technological solutions should conform to the community socio-cultural reality and meet real local needs, rather than attempt to implement scalable plug-and-play systems without knowledge of local community context [7]. Contextual engineering asserts that socio-cultural reality and real local needs are shaped by global drivers, such as historical conditions and identity issues; as well as local conditions, including geographic proximity to markets, resource accessibility, governance structure; stakeholder relationships, and processes [17,18]. It is a demonstration of the key principle that an understanding of, and an appreciation for, the social, economic, environmental, geographical, and political factors – the *context*, in short – should be considered integral to the design and decision making process [19,20]. Furthermore, to truly understand and appreciate context requires that design practitioners confront their personal predispositions and biases, and acknowledge the underlying relational and historical conditions that can affect the nature of stakeholder interactions [18].

This article uses a contextually-informed exploratory data analysis approach on an illustrative case study to argue that pre-selection of a technological solution on the basis of its ability to meet a perceived need circumvents a critical appraisal of the real needs of a community, which are heavily determined by the uniqueness of context. Social acceptance of a renewable energy technology is determined not only by the merits of the technology, but the end use application for which it is deployed. Examining the end use application with a focus on productive use in a given context can therefore be beneficial. In addition, technological intervention programs should also recognize their responsibility to adhere to processes and practices that are specific to the context of the end user communities. These programs should critically assess their procedural aspects, including an obligation to operate within extant institutional paradigms, develop and maintain a long-term support network, and engage in good faith trust building within a community for the long-term, with a focus on transparency and information sharing. The critical evaluation of these aspects are particularly relevant when working in rural communities of indigenous heritage, where distinctiveness of social, political, and cultural practices are shaped by a sense of identity and historical developmental trajectories.

The presented case study investigates two programs which provided renewable energy-powered technological solutions to address water and electricity access issues for remote residents in a resource-constrained indigenous community. The community is the Bodaway Gap administrative division (or chapter) of the Navajo Nation in the southwestern U.S., and the two technological solutions under study are solar home systems (SHS) and PV atmospheric water generation (AWG) systems. The systems share some technical commonalities. They are both powered using renewable energy (PV); have battery energy storage capability to provide continuity in service when the primary energy source is not available; are modular; and are "infrastructure-free" in the sense that they do not require any physical connection to a larger utility network. Each program, however, used a different deployment and engagement process. The investigations focus on a qualitative comparative analysis of the programs, the needs they were deployed to address, their performance, community members' perceptions of the programs, and how sustainable they were in terms of use and upkeep.

This case study analysis highlighted four factors that influenced social acceptance within the particular community:

1. An understanding of the productive use of a technology in context,
2. The need to operate within extant institutional paradigms,
3. The capacity to develop and maintain a support network, and
4. The need for trust-building.

These factors are conceptualized as falling into two categories: technological appropriacy (productive use in context), and procedural appropriacy (operating within institutional paradigms, support networks, and trust-building). A critical consideration of these four implementation factors during program planning provides valuable insights on the appropriateness of interventions in specific communities. While certain aspects of these factors have been previously highlighted in literature [21–24], the findings of this particular case study provide some refinements and additional perspectives to these factors from an application-oriented standpoint.

While the concept of productive use of energy has previously been conceptually identified [21,25], the additional qualifier "in context" is added to advocate for an expanded view of productive use. It serves to make explicit that productive use of a technological application cannot be pre-determined based on a designer or deployer's perceived needs of a community, or the technical need a solution is designed to address. Instead, the community members' rank order of priorities and lived experiences drives its determination. To that end, the idea of substitutability is presented as a test to determine a technological solution's productive use in a given context.

Similarly, the importance of the recognition of extant institutional paradigms has been presented before [24,26]. This article emphasizes a program's responsibility to operate within these paradigms by highlighting the reality that rural and indigenous communities develop unique modalities and processes to wield their authority in strategic stakeholder interactions. Consequently, a prerequisite for social acceptance within such communities is that any technological deployment appreciates and abides by these processes.

The need for establishing support networks has been identified as a key enabler in successful outcomes with regard to technology deployment [14,27], and the findings of this case study suggests that the willingness to develop and maintain a support network is closely tied to stakeholder motivations. A donor organization, as a stakeholder, must critically evaluate its motivations in participating in the program, and whether these motivations are concordant with the time and resource commitments necessary to monitor outcomes and provide support for the long term.

When working with indigenous communities, transparency in information sharing is a prerequisite to developing trust [28]. The need for trust building emphasizes the obligation for transparency in decision making and information sharing. It is particularly critical in interactions characterized by unequal power dynamics, such as indigenous communities that have been historically disadvantaged by socio-economically dominant exogenous groups. The findings of the case study suggest that lack of transparency in information sharing and insufficient representation in decision making can affect communal confidence in processes or institutions.

The case study also provides some general findings of the appropriateness, long-term viability, and limitations of donor-funded programs that deploy novel technological solutions in resource-constrained societies.

The remainder of this article is organized as follows. Section 2 draws from literature to highlight the challenges of the social acceptance of energy systems, including variations across scale, history of technological interventions, and differences in stakeholder priorities. Section 3 provides information about the data collection and analysis methods. Section 4 presents a detailed description of the case study community, its specific access issues, the extant processes and means used to navigate these access issues, and the interventions deployed to address them. Section 5 reports on the findings of the case study. Section 6 provides an analysis of the specific challenges that are observed in this particular case study, and uses the findings to expand upon the four factors described before, so as to situate them in the broader general discussion concerning social acceptance in similar contexts. Finally, Section 6 provides some concluding remarks.

2. The need to understand and appreciate societal context

Insufficient consideration of the social aspects of society within which users operate often comes about due to the primacy of technology driving the design process in the design practitioner's mind. Technology is often assumed to be neutral, and its users are conceptualized as "ontologically isolated", i.e., they are often assumed to interact with technology on an individualized, totally rational basis [15]. When operating under this premise, design practitioners are likely to explain away any resistance encountered during deployment of technical solutions as irrational, apathetic, or socially undesirable behavior [7]. The undeniable reality is that technology and society are closely linked, and how a technology gets accepted and adopted by a society and culture is deeply connected with the community's ethos [12]. Cultural acceptance is a complex social construct, though its conceptualization in the engineering design process is still rudimentary [29]. Acceptance spans across scales, i.e., the specific contextual factors that determine the attractiveness of technological solutions at policy making levels are not necessarily the same factors that end users consider when evaluating a technological solution. The zero-emission attribute of renewable energy, for example, is a central aspect in decision making at national levels, but the same attribute may be of less concern to a technology's users at localized urban levels. Users may be more concerned with who operates the systems, how much they cost, and where the systems are installed, as suggested by a study of South Korean consumers in [30]. Similar studies performed in Europe [29] provide instances where identified "desirable" factors differed significantly between national and local levels. Such variations and divergences between developmental needs and priorities at the national and local levels can negatively affect equity in energy access [31], often the same goals that a project is attempting to address. The misalignment between goals of technological solution advocates and socio-technical needs of target populations tend to occur when a problem boundary is prematurely defined based on a selective reading of the situation and stakeholder goals [32]. For rural and remote communities, these socio-cultural considerations are arguably even more important than in urban communities, since the social aspects become more significant in determining what solutions and support are needed and wanted [15,33].

A distinction must be drawn between the acceptance of technologies and the acceptance of technological solutions that use such technologies in a specific system. A renewable energy system incorporating solar PV and battery energy storage technologies can be utilized in a variety of end-user applications, such as individualized solar home systems (SHS), communal lighting, industrial usage, and information and communication technology (ICT)-specific uses, each of which is distinct at a system level. But while a community may be favorably predisposed in broad terms to the idea of solar PV and energy storage technologies, it cannot be construed to imply that they will naturally accept a specific technological system that incorporates these technologies. The appropriacy of a technological solution is determined by the end-user application to which the technology is applied, and whether that application is necessary, relevant, or useful for the context of the community. The community's perspective is the principal driver which determines the value of a technological solution for a given context, and this perspective is informed by their lived experiences and rank order of priorities [32]. A positive judgment of a community to any project or technological intervention is connected to the perception of getting benefits [22]. This focus on the *perception of benefits* is highly suggestive, as it makes explicit that the notion of what constitutes *benefit* is highly variable, and is community-centered. The current debate around productive use of energy is one of many such examples that illustrate an ever-evolving understanding of the perception of benefit. A review of productive use [21] relies upon the working definition of productive use of energy as one that results in goods and services with monetary value, enabling income generation. Cabraal et al. [25] point out that this traditional definition of productive use of energy is somewhat narrow and restrictive, and a wider reading of productive use of energy should emphasize its impacts on education, health, and gender issues. Abdelnour et al. in their study of cook stoves [32], go further by asserting that productive use is determined principally by what constitutes "productive" in the eyes of the community of users, which in turn is based on their situational context.

In addition to a technological intervention's socio-technical facet of productive use, there are procedural aspects of technology deployment that influence social acceptance. The acceptance of technological solutions in communities is heavily dependent on the history, successes, and failures of past projects of substantially similar nature [34]. These concern issues of trust [22], risk of social exclusion [35], and adequate level of collaboration of all stakeholders involved [36]. Even when landscape influences across different communities are similar, institutional forces and interactions play a significant role in shaping the appropriate developmental pathways of energy technology adoption [37]. Acceptance of local renewable energy systems can also be positively influenced by local political and economic participation [38]. Decision making regarding technological solutions and their applications in such contexts, then, should incorporate the general precepts of "what is necessary, what is affordable, what is feasible, and what is acceptable" [33].

The observations from Bodaway Gap have broader implications concerning the social acceptance of energy systems across other Native American territories within the United States, as well as indigenous communities throughout the world. The Navajo Nation is one of 334 tribal nations in the United States with designated federal- or state-recognized reservations or trust lands. Nationwide, these tribal lands – covering approximately 404,685 square kilometers [39] – are home to an estimated 1.14 million people [40]. With a resulting aggregate population density of 2.8 persons per square kilometer, these communities comprise a predominantly rural and remote demographic. Hoicka et al. provide a similar picture in Canada, which recognizes more than 630 First Nation communities (collectively comprising about 1.67 million people), 292 of which are off-grid [24]. These indigenous communities, due to various historical treaties, have come to exist as sovereign nations with a right to autonomy and self-determination. One of the ways in which they exercise this right is by governing their internal affairs in concordance with their traditional value systems. Consequently, external agencies working in these specialized contexts will invariably encounter political structures, context-specific knowledge, and cultural worldviews that are distinct from their own. Practicing in such contexts requires the recognition that many of the causal links between specific social behaviors and the ability of technological innovations in addressing needs can no longer be considered axiomatic [41], thus highlighting the limitations of technological innovation. Furthermore, acceptance within indigenous communities is also affected by social, material, and legal barriers that are deeply rooted in settler colonialism [23], which can be described as an ongoing process defined by unequal relationships where external groups locally and permanently replace indigenous ones [42]. Having been historically subjected to significant assimilation pressures, subjugation, and marginalization by exogenous socio-politically dominant groups, indigenous communities place much emphasis on the procedural aspects of technological intervention, by exercising their political control and authority when dealing with renewable energy projects within their communities [24].

3. Methods

The data for this study was collected via two major channels: literature research and review, and on-site fieldwork involving site surveying and participant interviews. The data collection was to develop an understanding of the utility access landscape and conduct a needs assessment for water and electricity within the community. Methodologically, the data collection followed the general precepts of contextual engineering [20], focusing on developing an awareness of the population needs; attestation of on-the-ground needs and its connection with socio-cultural reality, physical geography, and infrastructure; and an assimilation of attested information from the perspective of the user community [41,43]. The literature research and review involved trawling academic and grey literature in the public domain related to population demographics and distribution, water and energy resource availability, water and energy infrastructure, and historical policy landscape in Bodaway Gap, in particular, as well as the Navajo Nation, in general. Sources of documentation included:

1. Institutional reports from U.S. federal government agencies, including the United States Geological Survey (USGS) [44], and Bureau of Indian Affairs (BIA) [45];
2. Institutional reports from the Navajo Nation government agencies [45,46];
3. Presentations and publicity materials from the Navajo Tribal Utility Authority (NTUA) [47–50];
4. Technical reports and white papers from federal research agencies [51–53], or other professional organizations [54];
5. News articles from tribal [55,56], regional [57,58], and national media outlets [59,60];
6. Census and demographic data from national and tribal government databases [61,62]; and
7. academic research articles pertaining to electricity and water access issues in the Navajo Nation [63,64].

For the fieldwork phase, interview instruments were developed to focus on three principal topics:

- water — availability, means and cost of access, usage behaviors, and contingency measures;
- electricity — availability, means and cost of access, usage behaviors, and contingency measures; and
- community governance — forms of engagement with local representatives and other government agencies.

The interview instruments were a combination of descriptive and perceptive questions, conducted in a semi-structured fashion. The interview data served to corroborate access issues as highlighted in the literature review with that of the community members' perspectives. Logistically, participants were recruited through verbal announcements by Bodaway Gap community leaders at chapter meetings, posted signs at public offices and communal gathering areas, as well as by verbal referral through friends and family (snowball sampling). An on-site workshop on renewable energy technology was also used as a forum for observation and recruitment. Fieldwork was performed over the course of three week-long trips: May 2022, October 2022, and May 2023. Participant interviews were audio recorded (where feasible) or recorded in field notes. These were subsequently transcribed for thematic analysis. General notes and observations were also recorded of topics brought up in informal conversations in social gatherings. Emergent patterns from the analysis were used to develop initial impressions regarding patterns of behavior, usage, and access issues, and community perceptions, which were then cross verified through more targeted questions. The comparative analysis focused on identifying salient aspects of the electricity and water access issues, and to identify renewable energy technologies currently extant within the community to address them. Each technology solution was evaluated against current behavioral practices and logistical processes used to access electricity and water services. These technologies were evaluated against any additional criteria that were uncovered through the thematic analysis.

4. The case study: Electricity and water access in the Navajo Nation

4.1. The access issues in context

The Navajo Nation is the largest of the sovereign Native American territories within the U.S. and was originally established as the Navajo Indian Reservation through the Navajo Treaty of 1868. The majority of the Nation straddles the states of Arizona and New Mexico, with a small part in the state of Utah. It is subdivided into five agencies, which are roughly equivalent to a U.S. county in the administrative sense. These agencies are further subdivided into chapters (equivalent to a U.S. municipality), with a total of 110 chapters in the entire Nation. Bodaway Gap Chapter, in the Western Agency, is the largest chapter in the Nation. The Nation covers an area of 27,413 square miles, and had a resident population of 165,158 in 2020 [61], down from 173,667 as of 2010 [65]. It is very sparsely populated, with an approximate population density of six people per square mile. Situated in the predominantly arid southwestern region of the U.S., and being sparsely populated, the Nation has historically had difficulties accessing water and electricity services. The low population density is a reflection of the fact that the Navajo have traditionally been a herding society, and the semi-arid landscape necessitates large tracts of grazing lands for their livestock herds. As a result, homesteads on the Nation are spread far and wide [52]. Sheep raising has been an integral part of their lifestyle for generations, though there has been a growing practice of cattle raising for economic reasons [63,66]. This is particularly true for Bodaway Gap, where livestock raising forms a major economic activity. Most of the grazing lands in the Chapter are located close to the western boundary, near the Colorado and Little Colorado Rivers, as can be seen in Fig. 1.

The Navajo Tribal Utility Authority (NTUA), a tribal enterprise of the Nation, is the primary utility within the Nation, and is responsible for providing water, natural gas, electricity, cellular communications, and wastewater services to its residents. Due to the very high costs associated with *last mile connectivity*, most community members who do not live close to major transport thoroughfares–where most of the utility electric and water infrastructure is concentrated–do not have access to running water and electricity from the utility networks. Remote residents often rely on portable generators for their electricity needs, and haul water for their household and livestock needs. The water access issue is a bit more nuanced, because residents distinguish two separate functions and levels of quality for their water supply: potable water (PW) and livestock water (LW). Remote residents typically haul water from two different types of sources, depending on the type of need and time of year.

4.1.1. Treated potable water

The first type of source provides treated potable water (PW), reserved specifically for drinking and household purposes. Bulk PW supply sources are maintained by NTUA, and are supplied from its utility PW distribution network. They are card-operated, kiosk-type access points, an example of which is shown in Fig. 2(a), where residents pay a volumetric rate for the water they collect. Due to the persistent drought in the region, monthly limits have been placed at these access points

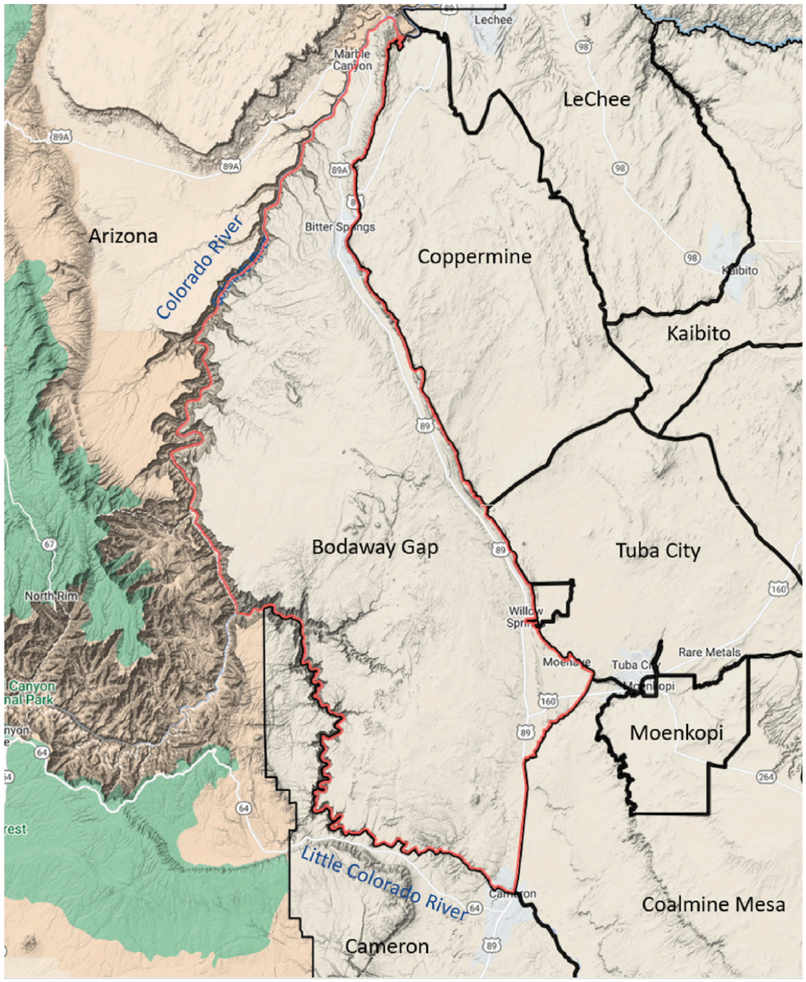

Fig. 1. A map of the western chapters in the Nation, with Bodaway Gap highlighted in red. The major transport thoroughfare is State Highway 89. The Western boundary of the chapter are the Colorado and Little Colorado Rivers, which also form part of the Nation's western boundary with Arizona.

(a) An NTUA drinking water access point.

(b) An earthen dam in the grazing lands.

(c) A livestock water filling station.

Fig. 2. The different types of water access points for the residents of Bodaway Gap.

to avoid overstressing the utility's water network. For contingency purposes, residents frequently stockpile drinking water, either in cisterns or in storage bottles in their homes. In the event their household water reserves run low before they are able to collect PW water again, they resort to bottled water for cooking and drinking, and minimize indoor bathroom usage by relying on dry pit toilets or outhouses.

4.1.2. *Untreated water for livestock*

The second type of source provides untreated water, specifically for livestock. These are typically managed by the Navajo Nation Department of Water Resources (NNDWR), though some are maintained by charitable organizations or family units. Livestock water (LW) sources fall under two categories: seasonal surface water and perennial

Fig. 3. A livestock corral in the grazing lands. The watering tank can be seen on the left side of the picture, and is filled with water hauled from LW filling stations during the dry periods.

groundwater sources. Seasonal sources are earthen dam reservoirs scattered throughout the grazing lands, an example of which is shown in Fig. 2(b). These capture and store seasonal precipitation during the wet periods of the year. Perennial sources of LW are groundwater-fed livestock water filling stations, an example of which is shown in Fig. 2(c). These are supplied from co-located wells. In Bodaway Gap, these sources are typically found along ridges near Highway 89, and are extremely rare in the grazing lands. These LW filling stations are particularly crucial to livestock ranchers during the dry seasons, when the earthen dam reservoirs dry up. During the wet season, residents usually only need to haul PW water, as their livestock can access water from the earthen dams. During the dry season, however, they haul water from the livestock filling stations to fill storage tanks located near their livestock corrals, an example of which is shown in Fig. 3. The filling stations do not typically limit the amount of water that can be collected, but it is not uncommon for them to close for refilling when demand draws down supply.

This is the context of the water and electricity access issue of the residents of Bodaway Gap. To address these access issues, two programs were implemented by two different organizations. The details of these programs are given in the next subsection.

4.2. Technological solutions to address water and electricity access

To address the electricity needs of the remote residents of Bodaway Gap, the NTUA has an off-grid solar program that provides residents with stand-alone, skid-mounted solar home systems (SHS). It is a long-standing program, having been piloted in 1993 [52]. The currently distributed version of these systems, an example of which is shown in Fig. 4, is rated at about 1 kW and consists of an array of solar panels (sometimes augmented with a small wind turbine) and a battery bank, generating between 2–3 kWh of energy per day [51,52], which is sufficient for basic lighting, charging cell phones, and powering an energy-efficient refrigerator [47]. The SHS are provided under a subscription model, and the monthly charge covers semi-annual preventative maintenance and repair services, which include parts and labor for the duration of the system's 15-year useful life. Semi-annual maintenance involves adjusting panel incidence angles for summer and winter insolation, and testing to ensure all components are operating within specifications. The NTUA retains ownership of the unit for its entire expected life, and also takes responsibility for appropriately disposing of it at the end of this period. The monthly charge for these SHS units is $84, plus applicable taxes [48], for a total of about $95, as indicated by community members.

To address the PW water needs of unserviced residents, a privately funded donor program was introduced in 2020, during the height of the COVID-19 pandemic. It provided remote homes with solar-powered atmospheric water generation (AWG) units, called Hydropanels, developed by SOURCE [67]. Fig. 5 shows two such installations in households on the grazing lands. These AWG units extract moisture from the air by drawing in ambient air and condensing it through a specially designed, proprietary hygroscopic material. The condensate is mineralized internally to provide clean drinking water with a desirable taste profile [67]. According to the technical specifications of these units, the drinking water output meets or exceeds U.S. Environmental Protection Agency's (EPA) and World Health Organization (WHO) standards for drinking water. The units also include battery energy storage and a water storage tank, so that water production is not interrupted during cloudy days [68]. A single Hydropanel unit measures 4 ft by 8 ft. A standard two-panel system costs approximately $5500–$6500, including installation costs, and produces about 4–10 l of water daily, though production is dependent on climatic conditions such as available solar insolation and air relative humidity. In partnership with Navajo Power, a public benefit corporation, and with funding through Barclays and The Unreasonable Group, 15 AWG systems were provided and installed on the Nation in 2020 as a pilot project [69]. Bodaway Gap was one of the recipient chapters.

Fig. 4. An NTUA SHS, provided under the off-grid solar program.

Fig. 5. Two separate installations of Hydropanels in Bodaway Gap.

The next section details a collection of findings on the usage and opinions of the SHS and AWG systems installed in Bodaway Gap. These findings are based upon surveys and interviews with various community stakeholders, including chapter administration officials, community members, and other NGOs, as a part of a project to assess the water and electricity access issues in the chapter. A comparative analysis of both programs is presented based on the findings, and these provide some insights on whether programs that are to be implemented should critically and dispassionately analyze certain factors to ensure applicability in the given context. The outcome of the analysis can support decision making at the planning stage to determine the appropriateness of specific technologies in specific contexts.

5. Findings of the case study

5.1. NTUA solar home systems

In Bodaway Gap, as in the wider Nation in general, households without any electrical service often use gas-powered generators to meet their electricity needs. These are usually small and portable units, sufficient for basic lighting, charging cellphones, and powering a few appliances. For more energy intensive needs, such as heating and cooking, residents typically utilize wood-burning stoves. While the NTUA SHS units are not designed to support energy-intensive applications, they are a comparable substitute to the gas-powered portable generators. Owners of the SHS units generally reported satisfaction with its performance, while many residents who did not have one expressed a desire to obtain one for their needs. Owners also reported favorably on its operational reliability and ease of use. This seems to indicate that at least from a technical standpoint, the SHS units provide an acceptable method of providing electricity where no electrical infrastructure is accessible.

While the NTUA is a utility company, it is also a tribally owned enterprise that provides an essential service to the Nation. Consequently, it is considered an agent for the implementation of the Nation's developmental policy. Due to this quasi-governmental position, the NTUA works closely with the administrative agencies of the Nation's chapters, and there are established protocols of communication in place through which chapters may petition to obtain service extensions or improvements within their administrative jurisdictions. These petitions typically are performed via chapter resolutions enacted during public governance meetings. However, while a chapter can propose a list of locations or specific community members for electricity access improvements, the final decision on the improvements rests with NTUA, based on their internal feasibility studies.

Present and potential customers of the NTUA SHS units tend to acknowledge one common concern about the SHS program: its high monthly cost is a significant financial burden. The maintenance provision included in the monthly charge is an attractive proposition–since customers do not have to worry about the time or resources necessary for system repairs in the event of a malfunction–but the systems are considered expensive for the amount of power they produce. Based on monthly costs and daily energy production, the average price per unit of energy from these systems is approximately $1.05/kWh, while NTUA grid-connected customers pay an average retail price of $0.12/kWh [18], the latter of which is about at par with the price paid by retail customers elsewhere in the U.S. By comparison, a portable 1-kW gas generator, which consumes roughly 2 l of fuel to provide a comparable daily energy output, produces electricity for approximately $0.70/kWh, based on the prevailing price for gasoline fuel. Thus, by a price-of-energy metric, the SHS are about 50% more expensive than the next best alternative available to remote households.

The NTUA ascribes the high service cost to its standing as a nonprofit utility, asserting that it cannot justify subsidizing SHS monthly charges by raising rates on current utility customers [48]. Indeed, it is reported that even with the current monthly charges, NTUA does not recuperate the maintenance costs of the SHS program [63]. Due to its status as a nonprofit entity, and its inability to raise significant reserves through rate increases, much of its capital investments have historically been funded through grants and other appropriations from various U.S. agencies. Partly due to this, it has a limited number of SHS units available, which are provided on a first-come, first-served basis. High cost is an issue even with distribution line extension requests made by individual residents or the chapter administration. The NTUA reports distribution line extension costs of about $50,000 per mile, and often denies grid electric connections to customers on the justification that the utility will not be able to recover its capital expenses by providing service.

Partly due to these factors, there is some resentment among community residents towards the NTUA. Some potential customers who applied to the SHS program still have outstanding applications more than a year later. As an entity, the NTUA is perceived as bureaucratic, lacking initiative, and insufficiently transparent by many chapter residents. The high service costs give residents the impression that the NTUA is a money-making entity for the Nation, and that its practices are a form of price-gouging. The resentment towards NTUA is also aggravated by practices seen in its non-electricity-related utility services. Some community members have indicated that they requested NTUA for water quality tests of their potable water supply, but received no response. As a result, community members are generally of the opinion that NTUA administration is unresponsive and not forthcoming with information.

Nonetheless, the SHS program has been sustained because of customer demand, and off-grid residents continue to seek SHS units as a replacement for their portable generators, despite the higher incurred costs. The continuing demand for the systems, notwithstanding the high costs, are attributable to the fact that maintenance responsibilities can be delegated so that residents have one less thing to worry about in their daily routines, even if it means interacting with an organization they regard as noncommunicative and engaged in profiteering.

5.2. SOURCE atmospheric water generation systems

The AWG systems were provided to community members through a privately funded program at the beginning of the COVID-19 pandemic. Residents were approached by the donor organization with offers to install the systems on their properties at no cost. Manufacturer-provided specification sheets for the Hydropanel [68] show a predictive chart for the production potential of these units, shown in Fig. 6. For the climatic conditions of Bodaway Gap, shown in Fig. 7, the production potential chart can be used to compute an approximate average value for the water production per panel per day, which is shown in Fig. 8. Based on these computations, a standard system–comprising two Hydropanels–can be expected to produce 5 to 10 l per day (150–300 l per month), depending on climatic conditions. Discussions with owners of these AWG systems indicate that the actual production is typically well below these predictions. Owners have reported lower yields, with estimates varying widely: ranging from about one gallon (3.75 l) per day on the higher side, to about one cup (0.25 l) per day on the lower side. Wide variations in production have also been reported on a day-to-day basis, with one owner indicating that it can fluctuate between a half-gallon (1.9 l) and nothing at all. Reports regarding the quality of water produced by the Bodaway Gap units have been conflicting. While some owners have praised the quality of the water, comparing it to bottled water, others have reported undesirable tastes that were strong enough to make it undrinkable. The noise produced by the units during operation has also been reported as undesirable.

A common issue that residents have reported is the general lack of service-related support for the systems. There does not appear to be a clear understanding of whom to contact when repairs are needed. In Bodaway Gap, residents indicate they typically contact chapter administration when in need of assistance with provided equipment or services. Owners frequently look to the chapter for assistance with livestock management, water hauling, assistance with home site leases or repairs, and requests for electric services. Following this precedent, owners reached out to the chapter administration for help with repairs or servicing the AWG systems. For its part, though, the chapter reported it had not been engaged by donors during equipment deployment and thus could offer no recourse in the event that a system failed. As such, it was unable to assist community members with maintenance concerns. Some owners attempted to contact the manufacturer directly for service support and spare parts, but they were unsatisfied with the lack of follow-up. The apparent sub-optimal performance of these systems, based on what had been promised to them, has also affected owners' perceptions of the system's reliability and usefulness, and lack of a chain of responsibility or communication has only aggravated the issue.

In addition to the maintenance issue, a key point indicated by several owners is that the systems do not provide sufficient water to be useful for their needs. A community member's water quota at the NTUA-maintained public filling stations is 1500 gallons per month, according to community residents and NTUA officials. As indicated by community members, they pay about $4 for 500 gallons of PW water. Residents make trips to these filling stations once or twice a week on average, filling up truck-mounted water containers – typically 55-gallon drums or 300-gallon tanks – which they then empty into holding cisterns in their households. Compared to this existing process in place for PW water needs, the AWG systems' production appears to be insufficient. Under the most optimistic conditions, these systems can be expected to provide for about 5% of the monthly quota at the PW filling stations. Compounded by the daily variability of these systems, their marginal utility is perceived to be so minimal as to be effectively negligible, and owners have not found them to be an adequate substitute in a way that reduces effort or makes their daily routine easier.

This lack of meaningful utility is compounded by the specific nature of the water crisis and how it affects the community's existence. Discussions with community members and chapter administration indicate that while water access in general is an issue, the primary concern of most chapter residents on the grazing lands has been obtaining water for livestock. As previously indicated, a considerable proportion of chapter residents, and virtually all remote residents, engage in livestock herding as a primary economic activity. Herd sizes across the chapter vary by size and composition of animals, with estimates between 50–200 head of sheep. Cattle and other animals are counted in sheep-unit

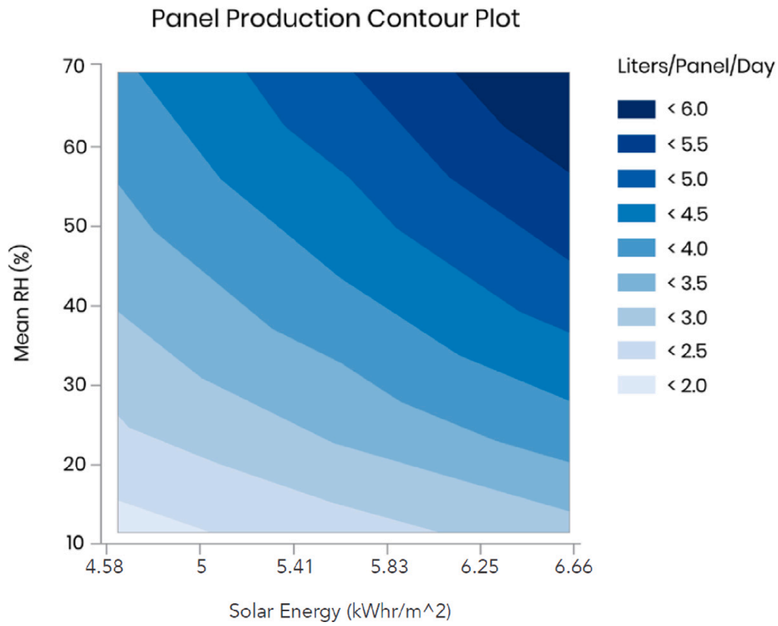

Fig. 6. SOURCE panel prediction contour chart, obtained from [68].

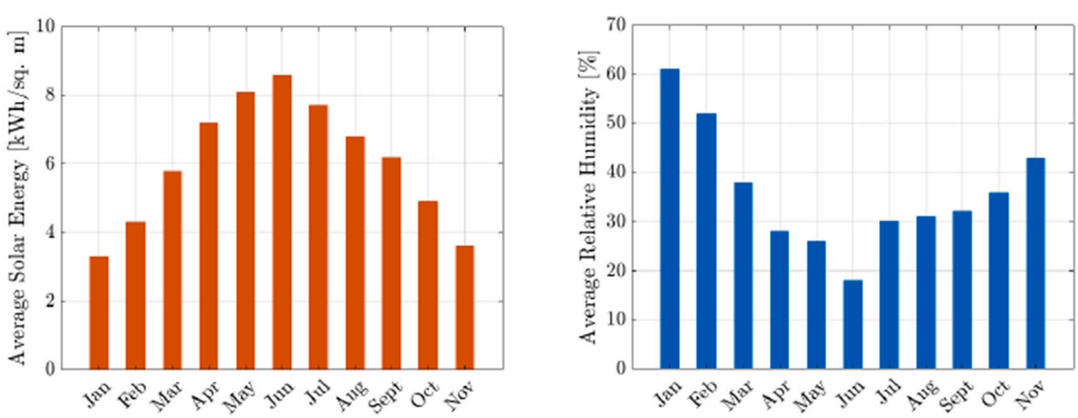

Fig. 7. Average monthly solar insolation (left) and relative humidity (right) in the Bodaway Gap Chapter. The data is from Tuba City, the closest monitoring location for which data is available.

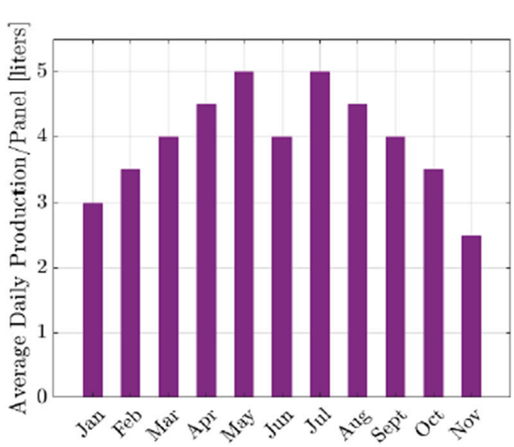

Fig. 8. Predicted average water production for Bodaway Gap site conditions.

equivalents. For their livestock, herders have to haul larger volumes of water than they need for their households, averaging about two to four 300–500 gallon loads per week. While there is some reprieve from having to haul LW during the wet season, herders may have to haul as frequently as every other day during the dry season. Climate change has also exacerbated the situation. Discussions with community elders indicate that in the past, reservoirs typically held water throughout the year, lasting through the dry season and until the monsoons, so residents only had to haul PW for household needs. In present times, with rainfall becoming increasingly unpredictable and rising temperatures increasing the evaporative losses, reservoirs have been running dry more frequently and for longer periods, necessitating more water haulage for a greater portion of the year.

6. Analysis: Productive use, institutional continuity, support networks, and trust building

Based on this case study, a collection of patterns emerges, which provides some insights on the key factors that influence the long-term viability and success of technological interventions put in place to address utility service access issues for the Navajo. These four factors are synthesized as follows: (1) understanding the principle of productive use in context, (2) ensuring institutional continuity, (3) establishing long-term support networks, and (4) focusing on community trust building. A shortcoming in adequately accounting for any of these factors during the decision-making stage may result in a deployed technological solution that does not effectively and sustainably address contextual need. While broadly consistent themes have been previously recognized, the findings of this particular case study provide refinements and additional perspectives to these factors from an application-oriented standpoint, focusing specifically on the themes of technological and procedural appropriacy. These four factors are presented herein.

(1) **Principle of productive use in context:** The concept of productive value is a powerful way to approach decision making in deploying technological solutions to meet a specific need [25]. Value is a reflection of true worth to people in the broad context of well-being and survival [70]. Productive use can be conceptualized as a functional form of value, and this conceptualization is advantageous in the decision-making process concerning technological solution deployment because it can be connected most tangibly to the intersection of context of people/place with the technical features/capabilities of the technology. In that regard, productive use in context can be thought of as *a practical use of a technology that enables useful activity, whether monetary, economic, cultural, or comfort, in a specific context, in ways that were either not extant before, or were inadequately met using existing resources and methods.* This conceptualization emphasizes the following key idea: that any technological solution introduced to a specific community context should provide meaningful productive value by supporting and strengthening members of the community to improve their living condition, over and above what could be achieved before. In addition, the presented idea also provides an understanding of the value of a technological solution in terms of its potential for substitutability. Specifically, if the technological solution is deployed to substitute or supersede a pre-existing solution or process, it should perform comparably while relaxing some aspect of operational constraint or complexity of the pre-existing solution or process. In the event that the new solution is a comparable substitute but incurs a higher effort than the extant solution or process, then it requires a comparative assessment of what productive use a user gains, and what they need to give up in order to gain it. Put equivalently, this conceptualization of productive use can be interpreted as an analysis of the marginal utility of a new solution over a pre-existing solution, whether the new solution relaxes some operational constraints compared to the pre-existing solution, and whether the cost incurred in adapting it over the pre-existing solution is commensurate with the utility it provides.

In the case study, the SHS and AWG systems provide good examples to illustrate the principle of productive use in context. The SHS units are able to provide a comparable substitute to an extant solution (portable gas generators), albeit at a higher cost. This undesirable high cost is somewhat ameliorated by a desirable relaxation of the maintenance constraints that are associated with the extant solution. Thus, from a productive use aspect, these systems find a willing customer base.

The AWG systems, on the other hand, do not provide meaningful productive use in terms of water access in the specific community context. Since the systems were provided at no cost, the issue of cost-effectiveness may be considered irrelevant, but utility remains a critical aspect to consider. While the systems can be considered an equivalent or even superior substitute for PW water from a water quality perspective, (based on the favorable comparison with bottled water, though this characterization is widely variable), they are not comparable substitutes to address the need for water quantity, especially compared to the extant process of water hauling. Additionally, the AWG systems are an insufficient substitute for LW, which was seen to be a prime concern in this specific context

(2) **Institutional continuity:** Rural and remote communities often exhibit social norms, governance structures, and operating paradigms that can be significantly different from those seen at urban and national levels, due to their resource-constrained conditions and unique developmental trajectories. For example, rural Andean communities heavily function on the principle of *ayni*, a social contract based upon reciprocity that creates a sense of obligation to assist another party in response to assistance rendered by that party previously [71]. *Ayni* is deeply culturally ingrained, thus creating obligatory member participation paradigms in communal labor mobilization. Similarly, Basu [72] provides examples from rural India, where community members leverage social capital and expected standards of behavior in economic transactions to reduce the possibility of defaulting, thus illustrating the case where social norms cause market operations in these communities to function in distinctly different ways as compared to urban communities. Local community leadership tend to have a significant influence in communal power dynamics, and their participation and interest in the management of a technological deployment can be consequential in determining the ultimate outcome, as pointed out by Whaley et al. [26]. These are just some instances that highlight the reality that any outside technological intervention in such communities must recognize the existence of, and assimilate the knowledge of, these unique institutional modes of social engagement. Thus, technological solutions need to ensure that they establish a sense of continuity with existing institutionalized political, economic, and social practices and processes. Socially acceptable projects establish continuity with existing physical and social structures, and apply good communication and participation procedures [29]. The deployment of technological solutions should be accompanied by the establishment of clear chains of responsibility that are congruent with ones that exist within the community already, and these should be done in collaboration with all stakeholders involved.

The Navajo have some unique institutional modalities, which have a cultural and historical basis. Prior to European contact, Navajo people settled and lived in small, localized, and autonomous communities, and all decision making occurred locally. These systems of leadership were disrupted in the post-contact period. Recognizing that the historical paradigm of localized governance and decentralized authority continues to resonate strongly with contemporary Navajo communities, the Nation's central government enacted the Local Governance Act in 1998. Through this act, the central government delegates certain powers and authorities to local chapters [73]. Resolutions are a characteristic institutional mechanism in this devolution of powers, as they form the procedural basis of how local chapter leaderships exercise their sovereignty. These include issues of economic development, zoning, revenue generation, and infrastructure development. Resolutions can be proposed by chapter leadership, or even directly by community residents. Proposed resolutions that are passed by a majority of the present voting members serve as the chapter's official expression of community will.

In terms of the NTUA, while customers liaise with the NTUA as individual customers, the chapter administration can also advocate for its residents through chapter resolutions. The NTUA recognizes this institutional practice, and maintains channels of communication with chapter administrators to receive and deliberate upon such resolutions. Thus, the chapter administration possesses a certain political capital with the Nation's agencies that operate within its jurisdictions, and attempts to utilize its administrative authority to advocate for its constituents.

In contrast, the program that provided AWG systems to chapter residents does not appear to have engaged with the chapter.

Indeed, based on discussion with the chapter administration, it appears that the deployment of the AWG systems side-stepped the engagement process entirely. This lack of engagement compromised the AWG donor program in two ways. Firstly, it prevented the program from conducting a dispassionate analysis to determine whether AWG systems were productive solutions to the livestock-dominated water access issue of the community. Secondly, the deployment proceeded through a parallel organizational process that was politically unaccountable to the residents or their representatives. As a result, the chapter administration felt blindsided by the deployment, with the result that it perceived itself as being unable to leverage its political capital to advocate for the residents who encountered maintenance issues.

(3) **Support Networks:** Technological deployments should be accompanied by support networks that systematize and disseminate information of proper installation and regular maintenance practices and spare parts [14]. This is a major consideration in which many privately funded donor systems fall short. These types of deployments often are planned as a capital-intensive distribution of equipment, but insufficient consideration is given to the investment and efforts necessary for proper and regular maintenance, frequently because such considerations would require ongoing engagement, costs, and technical support. This tendency is exacerbated by the metrics and focus of the donors, which can differ from those of the community [31]. The issue is particularly acute in the supply-led (or top-down) development paradigm, where the developmental goals are primarily set by donors [74]. Measuring outputs (e.g., the number of completed installations) is a convenient metric for donor organizations since it provides rapid feedback on measures of apparent success, and serves as an indication that allocated resources are contributing to high levels of activity. Consequently, there is less appetite to engage in more costly longitudinal studies to focus on outcomes (e.g., quality of life improvements) which the technological intervention is meant to achieve.

In the case study, it was observed that the NTUA SHS program provided users with a comprehensive support network and set down a clear division of responsibilities between the customer and the service provider. Despite not recovering their maintenance expenses through the monthly charges, the NTUA continues to ensure that access to maintenance personnel, know-how, and parts are made available at regular intervals to the customers. This is perhaps another reason that the NTUA SHS program has found a willing customer base, despite the higher cost.

In contrast, there was no evidence that the AWG program invested in developing a support network to provide for information exchange, personnel, or spare parts procurement for maintenance. None of the users recalled receiving any meaningful training. Additionally, discussions did not indicate that any AWG system owners were aware of a formal support network that they could access. This would also explain why some residents tried to contact the chapter administration, while others tried to reach out to the manufacturer directly, all with unsatisfactory results. While the AWG system technical specifications indicate that the systems have provisions for remote monitoring via a wireless transmitter, it requires a constant local WiFi or cellular service [67]. The chapter grazing lands, however, have little to no cellular connectivity.

(4) **Trust Building:** Trust building is a key aspect of any type of population engagement in infrastructure development. For communities that have historically been marginalized or resource-constrained, self-perceptions of being deliberately overlooked by agencies purporting to serve them certainly can be appreciated. While lack of services is often due to the lack of economically viable means or methods, it is still incumbent upon the decision-makers within these agencies to clearly communicate their challenges to the community. Not doing so only heightens the perception of wanton neglect. Trust building requires time, a long-term presence, and the genuine recognition of the agency of the community members in choosing the means and methods most appropriate for their situational context [22,35], and to share information openly such that they may do so.

In the case study, it was found that the NTUA has continuing challenges with trust building in the community. Many of the institutional decisions it makes remain opaque to the community. While the outcome of the decision making follows from established and sound organizational protocols, the NTUA has fallen short on communicating the rationale of its decisions to community members. It was also hinted by some members of the community that they did not believe the NTUA's highest decision-making body has sufficient tribal representation, and that a majority of the body is composed of non-indigenous members. Publicly available information from NTUA does seem to validate this, as only three out of the seven members of the management board are identified as members of the Nation [75]. This further elucidates the need for trust building, and incomplete information exchange and lack of transparency are not conducive to this process. Nonetheless, the NTUA has been around for a long time, and so is more "familiar" than an unknown organization.

The AWG program appears to have suffered from this problem as well, except the lack of trust may have been caused by the fleeting nature of the program and the high promotional visibility of the donor during deployment. As a program that was donor-driven and focused on technology deployment, it does not appear to have devoted much effort in developing a long-term relationship in the community. The program appears to have been primarily focused on providing a very visible and promotable solution, and did not examine the context of prior technological interventions or what could be learned from past projects and the situational context of the present community members.

7. Conclusion

The findings of the case study and the drawn conclusions provide generalizable knowledge to add to the body of existing work on the social acceptance of energy systems in rural and indigenous communities in other parts of the world. In particular, the insights from the case study led to a distillation of four key aspects that factor heavily into the decision making process of technological solution deployment, namely (1) an understanding of the productive use of the technology in context, (2) the need to operate within extant institutional paradigms, (3) the capacity and inclination to develop and maintain a support network, and (4) the need for trust building. The four factors broadly align with similar themes that have been identified in literature before, and the findings of the case study provide the basis to propose refinements to these themes, particularly from an application-oriented perspective. The factors can broadly be classified into two categories related to the appropriacy of a technological intervention: technological appropriacy, and procedural appropriacy. Technological appropriacy, evaluated through the lens of productive use in context, demonstrates how a thorough needs assessment is necessary so as to fairly and dispassionately evaluate whether a specific technological solution is appropriate in a given context. The idea of substitutability is presented as a concept test to better understand whether a technological solution serves a productive use in a given situational context. The procedural category concerns the obligations of a technological intervention to operate within institutional paradigms of stakeholder interactions, to develop a long-term support network, and to build trust among community members through open information sharing as it concerns decision making.

The findings of the case study also serve to highlight the idea that novelty of technology does not correlate to an ability to address needs. Indeed, it shows that the technical merits of the technology *in and of itself* play a relatively minor role in the predictability of successful outcome. While adequate technical performance is a necessary prerequisite for a successful outcome, it is by no means a sufficient one. The social context within which technology is deployed is far more crucial to understand and appreciate, and how well the deployment can navigate and serve the specific social context is a far superior predictor of a successful outcome. Specifically, the case study provides the basis to state that the ability and willingness for any technological intervention to recognize, appreciate, and abide by extant institutional paradigms that govern stakeholder interactions within a community have a great bearing on whether technological interventions are likely to be socially accepted.

Another key insight that the case study provides is an understanding of why donor-provided systems that focus heavily on technological deployment can perform poorly in the field. Donor-provided systems work with fairly short timelines, with the planning stage focusing on capital expenses. As a result, insufficient consideration is given towards the more time-consuming and incremental – but very vital – tasks of maintaining a presence critical to trust-building and for long-term support. The lack of planning for these social needs has major implications on the sustainability of the technological deployment in the long-term. It may also be noted that it does a general disservice to all future technological interventions as well. Failure of a specific instance of technology deployment affects not only that particular intervention, but all successive interventions by other organizations, by creating a precedent as to what may be realistically expected from similar interventions in the future. The persistence of this precedent in the collective memory of a population subconsciously influences the development of a communal preconception toward any subsequent program that is executed in a similar way. As such, future interventions are burdened with the task of undoing past expectations before any progress can be made in the present. NGOs and other donor-led programs implementing climate resilient solutions in communities can thus improve the sustainability and effectiveness of their programs by re-calibrating their programs to put a greater emphasis on outcome — rather than output, a calibration that will require a dedication towards monitoring and assistance for the long term.

Declaration of competing interest

The authors of this article are presently conducting research investigations into water and electricity access issues in the Bodaway Gap chapter of the Navajo Nation. The findings from the investigation will be used to assist an ongoing developmental effort to improve water access in the community. The work undertaken in this investigation is not believed to conflict with any previous developmental effort in the chapter.

Data availability

Data will be made available on request.

Acknowledgments

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