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Perspective

Beyond money: A social burden framework to enhance resilience valuation for tribal communities in the United States

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ABSTRACT

This article reflects on the present challenges of making proactive investments in critical infrastructure resilience and proposes recommendations for better integrating non-financial benefits into investment and project financing decision-making. Quantitative methodologies are required to enable communities, utilities, and financing organizations to evaluate return on investment through a more complete, socio-economic lens that more fully captures the true returns of alternative resilience proposals. Although this need is universal, it is further exacerbated in historically disadvantaged, under-resourced, and disenfranchised communities which were excluded from large-scale federal-level infrastructure investments in the past, and in which today, the onus of securing financing for infrastructure resilience projects falls on community members. This need is illustrated, and a solution for it demonstrated, through a case study of a successful implementation of such a techno-socio-economic resilience investment valuation framework in a tribal context.

1. The challenge of making proactive resilience investments

A bevy of natural and anthropogenic stressors – from natural hazards and resource limitations to supply chain interruptions and geopolitical instability, conflict, and population displacement, are at risk to disrupt critical infrastructure assets and systems that sustain lives and livelihoods [1]. Resilience is the ability to prepare for and adapt, withstand, and rapidly recover from disruptions; a definition which despite unique manifestations and different metrics, at its core has become widely adopted across many domains [2], with applications ranging from social (organizational resilience [3]; supply chain resilience [4]; community resilience [5]) to physical infrastructures [6]. Regardless of domain, resilience focuses on low-probability, high-impact events [7]. There are many challenges associated with resilience planning. In this article, we focus on the problem of resilience valuation.

Utilities collect extensive information on the costs of damages from resilience events after the fact, but struggle to justify preventative mitigation investments, in part because there is no standard, agreed-upon framework for valuing their social and economic benefits. Without proper valuation, it is difficult to justify resilience mitigations, as well as to identify what level of investment is "warranted". Existing methods for evaluating investments in resilience mitigation measures, and making go/no-go decisions about them, focus on direct financial impacts/benefits of the project. Although case studies exist (e.g., as described by Baarsma and Hop in the Netherlands [8]), existing market structures still predominantly do not incentivize utility investments in preemptive resilience mitigation measures, since damages from unmitigated, or under-mitigated, resilience events can be recovered by utilities through rate increases (e.g., as in Texas, USA in the aftermath of Winter Storm Uri in 2021 and Hurricane Beryl in 2024 [9]).

The need for effective resilience valuation metrics is universal. However, inequities in access to financial and political capital and access to baseline infrastructure, makes the urgency of resilience investments in some communities more acute while simultaneously putting the burden of securing these projects on community members. To illustrate this in practice, we highlight the experiences of the Iowa Tribe of Kansas

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and Nebraska using a real-world case study. The Iowa Tribe of Kansas and Nebraska (ITKN) is a sovereign nation and one of 574 federally recognized Indian Tribes in the United States. The ITKN have faced many energy challenges including frequent power outages that have left the community without power for up to 60 or more days of the year [10] and impacted resident health, safety, and social and economic well-being. The impact of these power outages is exacerbated by the remoteness of the reservation, which is 20 miles from the nearest town. When limited on-reservation infrastructure assets lose power, residents have few nearby alternatives for food, fuel, medical care, communications, and other critical services. ITKN has developed multiple alternative microgrid designs to provide resilient power to the ITKN reservation's primary infrastructures. To move from planning to implementation, however, ITKN is reliant on obtaining public and/or private financing. Although the microgrids could result in some energy savings, those savings would not be sufficient to offset the capital costs and break even or return a profit. ITKN has experienced repeated difficulty obtaining both private and public financing for their microgrid proposals when the only quantitative, widely-accepted valuation methodology for describing the value of these resilience projects consisted of profitability indicators. As a result, communities become trapped in a vicious cycle where incentives are required to bridge the profitability gap, but those very incentives reward project profitability. This was the experience of the ITKN as well, until recently, when through the application of a social valuation of resilience framework, ITKN was awarded over $22.5 million in combined grant funding by the U.S. Department of the Interior and the U.S. Department of Environmental Protection Agency for microgrid construction and workforce development programming on microgrid installation, operation, and maintenance [11–13].

2. Progress in resilience valuation: Alignment and outstanding need

Much of the existing resilience valuation scholarship has focused on quantifying the economic costs of outages, particularly short-duration outages [14,15]. The concept of value of lost load (VOLL, usually measured as $/kWh) has gained wide traction, though there remains a high degree of diversity of approaches to its estimation and application, in particular for residential customer impacts, which are notable more difficult to standardize and monetize than commercial and industrial accounts [16–19].

By contrast, there are fewer widely agreed-upon frameworks for the valuation of the social (e.g. non-economic) benefits of resilience, or the social (e.g. non-economic) VOLL. In part this is because unlike economic valuation metrics, the social (non-economic) resilience benefits do not lend themselves to a singular unit (e.g., $, or $/kWh), and so it is more difficult to compare them and make informed decisions about possible tradeoffs. Some frameworks for the valuation of social benefits of resilience have converged on a services-based approach that equates the value of infrastructure and its resilience to the value of the services provided by the assets to people. For instance, Clark et al. have proposed a services-based approach to valuation of the social benefits of critical infrastructure [20]. In the weatherization literature, non-energy impacts (NEIs) or non-energy benefits (NEBs) are discussed [21]. These include factors as disparate as avoided emissions, reduced water and sewer demand, improved comfort, and reduced stress – focusing on the value to society provided by buildings and the incremental value added by their weatherization. By contrast, other frameworks for social resilience valuation have focused on capturing differences in people's experiences of and dependance on the natural and built environment, and the differing impacts from their losses. For example, in response to direction by the California Public Utilities Commission, the investor-owned electric utility Southern California Edison developed the Community Resilience Metric (CRM) and Community Impact Metric (CIM) [22] for evaluation and equitable prioritizing of climate adaptation investments. The metrics combine adaptive capacity and social vulnerability indicators into a composite, numeric measure that allow the utility to compare the benefit of resilience investments in different parts of its 50,000 mile^2, 15-million customer service area. Fully capturing the valuation of social (non-economic) benefits of resilience requires the synthesis of both the services-based accounting of the value of infrastructure as well as the recognition of disparate experiences of infrastructure loss and the factors that contribute to them.

3. The social infrastructure service burden metric

Energy in of itself does not hold intrinsic value to its end users. Instead, its value is derived from the provision of goods and services that require power as an input [23]. In addition to power, these goods and services require infrastructure to enable their production and delivery. Thus, the provision of critical services in fact depends on both infrastructure and power availability. The Social Infrastructure Service Burden metric (abbreviated Social Burden) links these concepts and provides a common language for electric and non-electric infrastructure owners and operators, as well as local jurisdictions, to jointly plan and invest in community resilience.

The Social Burden metric is defined as the burden a particular individual or community face when seeking to obtain critical lifeline services provided by infrastructure. Infrastructure locations represent opportunities to acquire critical services that fulfill important needs, such as the need for food, water, shelter, healthcare, communications, or financial services, among others. Critical services are the linchpin between functions and benefits within the Energy Service Cascade [23]. Social Burden is concerned with the well-being context, or conversely, its lack, when energy is not available to power services that provide benefits. It is not enough for infrastructure to be powered in order for people to obtain critical services. Accessing critical services frequently requires travel effort, disruption to schedules, and expenditure of money. More affluent households, on average, use more electricity [24], and are willing to pay higher amounts for avoiding outages, so their perceived VOLL (and associated value of resilience mitigations) would be higher. Lower-income households spend proportionally more of their income on energy [25]; however, they may spend less overall, generate less economic turnover, and their foregone spending may be lower as compared to higher income households [15]. However, they may nevertheless be more impacted because they have fewer resources at their disposal to replace goods and services impacted by an outage.

Social Burden represents the relative hardship people experience while acquiring needed services, which is determined by the availability and accessibility of critical services relative to where people live, and modulated by an equity criterion that captures relevant demographic differences that make some members of a study area more (or less) challenged by travel and acquisition of goods and services. Social Burden is defined in detail, including application in communities and validation, in several publications [26–30]. Notably, Social Burden has also been successfully combined with other independent alternative social resilience valuation frameworks, such as the CRM, to inform climate adaptation investments by electric utilities [30].

Conceptually, Social Burden may be described as:

$$Social\ Burden = \frac{Effort}{Ability}$$

Which in practice is estimated as:

$$Social\ Burden \cong \frac{Distances\ to\ Services_{people,services}}{Service\ Levels_{facilities,services} \times Attainment\ Factor_{people}}$$

Social Burden is a spatially explicit metric in that it represents the exact geographic location of each facility providing critical services and each population sub-group polygon in XY space. Social Burden is calculated for the many-to-many distance matrix between all population

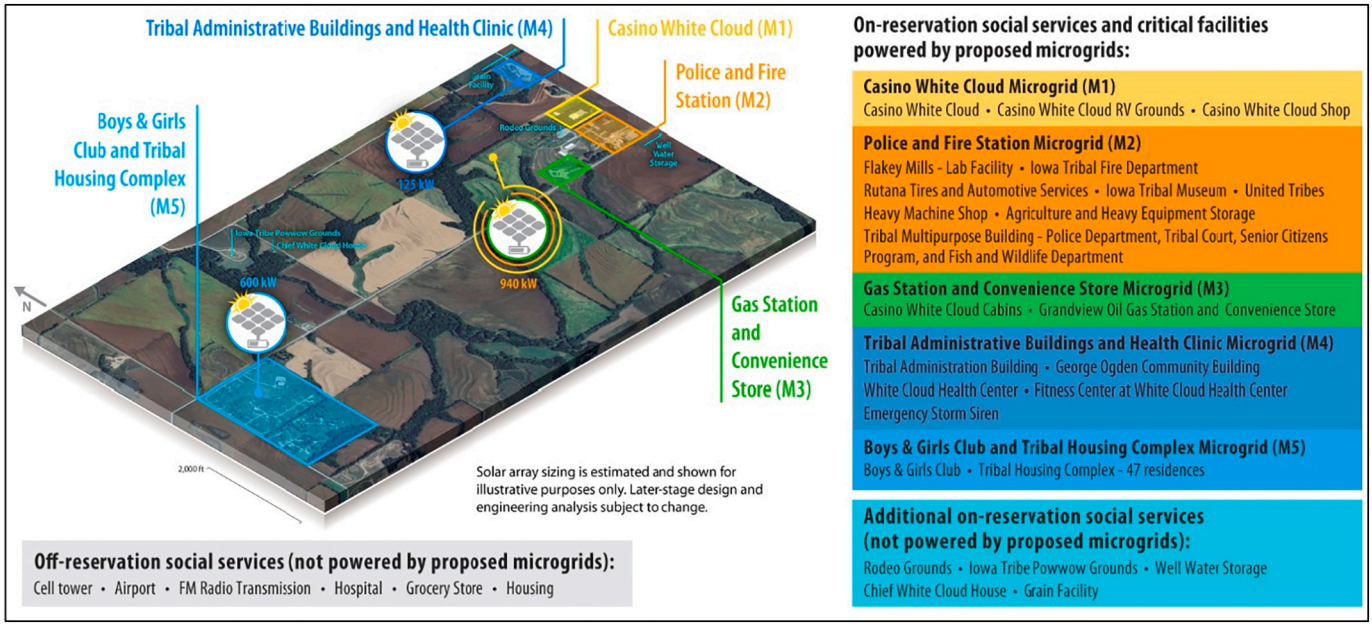

Fig. 1. Proposed configurations for five alternative clean energy microgrids (M1-M5) for the ITKN.

Table 1
Preliminary Modeling Results for Microgrid Component Sizing.

Microgrid	Annual Consumption (kWh)	Annual PV Production (kWh/year)	PV Capacity (kW^{dc}/kW^{ac})*	Battery Capacity (kW/kWh)	Generator Capacity (kW)
M1**	1,720,000	1,045,000	700/600 (1-axis)	300/1200	500
M2	220,000	210,000	140/125 (1-axis)	50/100	75
M3	155,000	145,000	100/80 (1-axis)	50/100	45
M4	170,000	155,000	125/100 (Fixed Tilt)	50/100	75
M5	760,000	740,000	600/600 (Fixed Tilt)	300/600	500

* kW^{dc}: PV array capacity,
*kW^{ac}: PV inverter capacity
** PV capacity for M1 constrained by 200 kW export limit. For the other microgrids, the PV is sized so that annual PV production roughly matches annual consumption.

sub-group polygons and facilities providing critical services in a study area, such that each population sub-group has a unique Social Burden score associated with each critical service, as well as all services combined.

Mathematically, the conceptual formulation is represented as:

$$SB_{n,m} = \frac{E_{n,m}}{A_n},$$

Where:

$SB_{n,m}$ is the Social Burden, a matrix over discrete space composed of population sub-groups (n) and infrastructure services (m);

$E_{n,m}$ is the Attainment Effort, or how hard people work to attain their infrastructure needs, also an n x m matrix;

A_n is the Attainment Ability, or the resources people have at their disposal for attaining their infrastructure service needs, not dependent on the type of service, a vector of length n.

Effort (E) is a function of the individual "pairwise efforts" between each spatial element (n) and each point that provides an infrastructure service (l), as follows:

$$E_{n,m} = \frac{1}{\sum_l S_{l,m} \Big/ I_{n,l}},$$

Where:

$S_{l,m}$ is the Infrastructure to Service relationship, a matrix of infrastructure locations (l) and infrastructure services (m);

$I_{n,l}$ are the individual pairwise efforts between spatial elements (n) and infrastructure points.

Social Burden is never zero. "Blue-Sky" Social Burden is the baseline when all available infrastructure is functional and powered and providing critical services at their maximum potential levels. "Black-Sky" Social Burden is unique to each alternative infrastructure disruption scenario, when certain infrastructure locations lose power and/or are damaged, and their ability to provide critical services is reduced. Existing or hypothetical outage mitigation or adaptation measures can be included in a "Black Sky" scenario by reducing the extent or duration of critical service loss during an outage. The Social Burden differential is calculated as the difference between the "Black-Sky" and "Blue-Sky" Social Burden scores. The value of alternative resilience measures can be measured by comparing their ability to decrease Blue-Sky, Black-Sky, or Differential Social Burden so that the impacts of large-scale disasters and

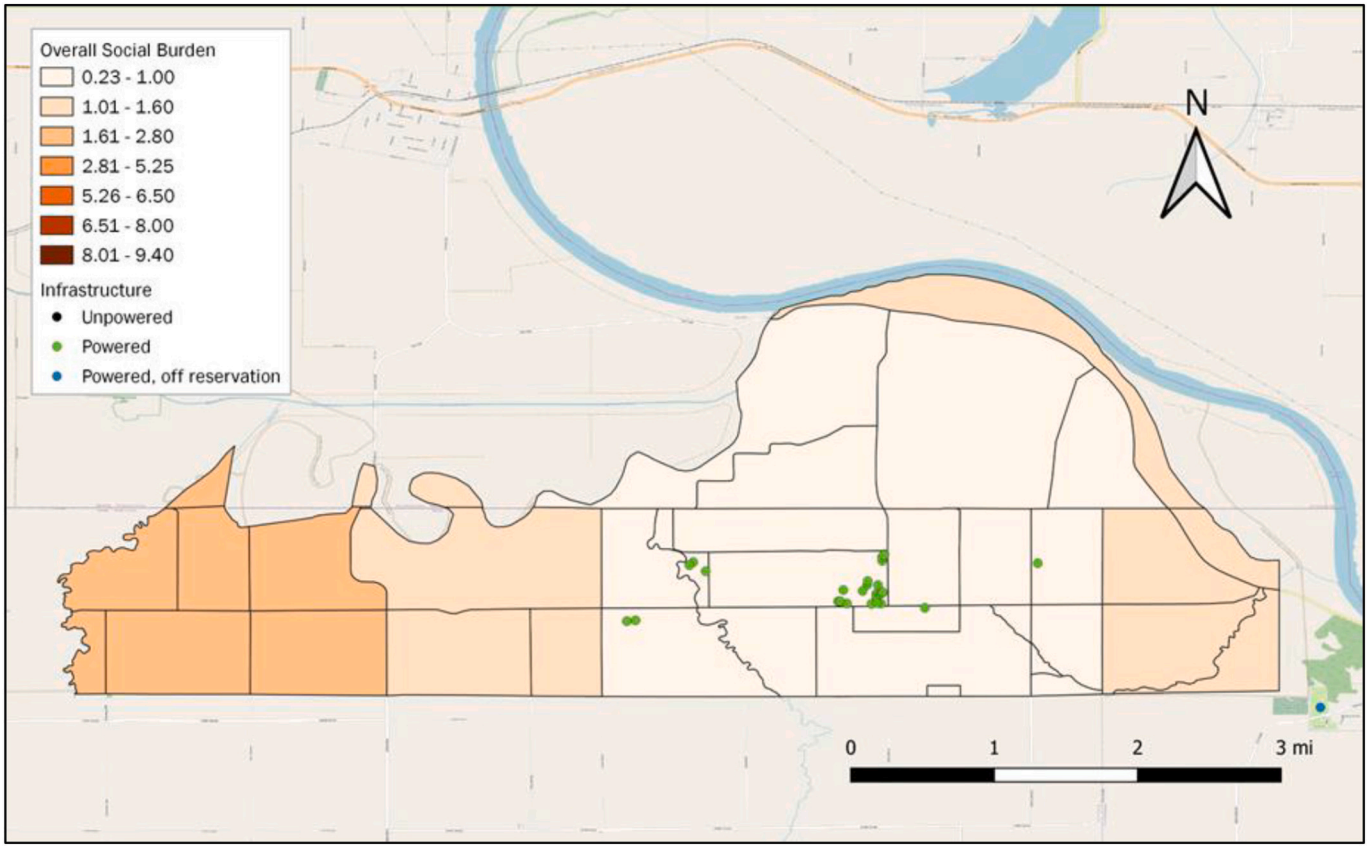

Fig. 2. Per-Capita Social Burden distribution under a "Blue-Sky" scenario, with normal grid power. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

extended duration power outages would be less severe.

4. Application of non-economic resilience valuation: Case study of social burden in action

The Iowa Tribe of Kansas and Nebraska (ITKN) is a sovereign nation and one of 574 federally recognized Indian Tribes in the United States. The ITKN is located along the Missouri River on the border of northeast Kansas and southeastern Nebraska. Over 800 people (tribal citizens and non-tribal residents) live on the reservation, and approximately 500 more visit or work on the reservation daily. The ITKN have faced many energy challenges including frequent power outages that have left the community without power for up to 60 or more days of the year [10] and impact resident health, safety, and social and economic well-being. The impact of these power outages is exacerbated by the remoteness of the reservation, which is 20 miles from the nearest town. When limited on-reservation infrastructure assets lose power, residents have few nearby alternatives for food, fuel, medical care, communications, and other critical services.

Under the Rural Electrification Act of 1936, the U.S. government provided financial incentives to help utilities and newly formed co-operatives bring electricity to far-flung farms and towns. Yet the movement largely bypassed Native American lands [31]. As a result, many households on rural US reservations are either not connected to the electric grid or are end-of-line customers of one or more rural utilities and co-ops centered elsewhere. They experience higher-than-average unreliable electricity access and may have higher-than-average energy burdens (i.e., a higher-than-average proportion of their income goes toward energy costs) [31]. This begets reliability and resilience challenges, such as the ones that ITKN has faced, and a gap in infrastructure investment that Tribes are actively striving to fill in present day while simultaneously looking to leverage local clean energy resources [32].

The long-term energy goals for the ITKN are centered around achieving energy sovereignty. Priority actions include the establishment of a Tribal Utility Authority (TUA) to promote social welfare and community development, and the deployment of renewable community microgrids and sustainable energy storage systems to enhance ITKN's resilience to power interruptions. A microgrid is a small-scale version of an interconnected electric grid and can locally manage distributed energy resources such as photovoltaics, wind, and energy storage. The microgrid can be an independent power system or can be connected to a larger host grid. A microgrid that is connected to a larger grid can provide continuity of electric power supply when the bulk grid is disrupted. Communities, especially end-of-line communities, are increasingly becoming interested in microgrids as an energy sovereign way to combat not only resilience concerns (low-frequency, high-consequence events), but increasingly, reliability concerns (high-frequency, low to moderate consequence events) as well. Microgrids are well-accepted solutions to energy resilience and have demonstrated their utility in responding to major events [33]. However, the high upfront investment costs identified by Soshinskaya et al. [34] and the lack of access to capital and "split incentives" identified by Ali et al. [35] remain in effect. ITKN has designed multiple alternative microgrid designs to provide resilient power to the ITKN reservation's primary infrastructures. To move from planning to implementation, however, ITKN is reliant on obtaining public and/or private financing. Although the microgrids could result in some energy savings, they would not be sufficient to offset the capital costs and break even or return a profit. A compelling case could not be made based on the technical merits and economics alone, and the ITKN has experienced repeated difficulty obtaining both private and public financing for their microgrid proposals. ITKN's

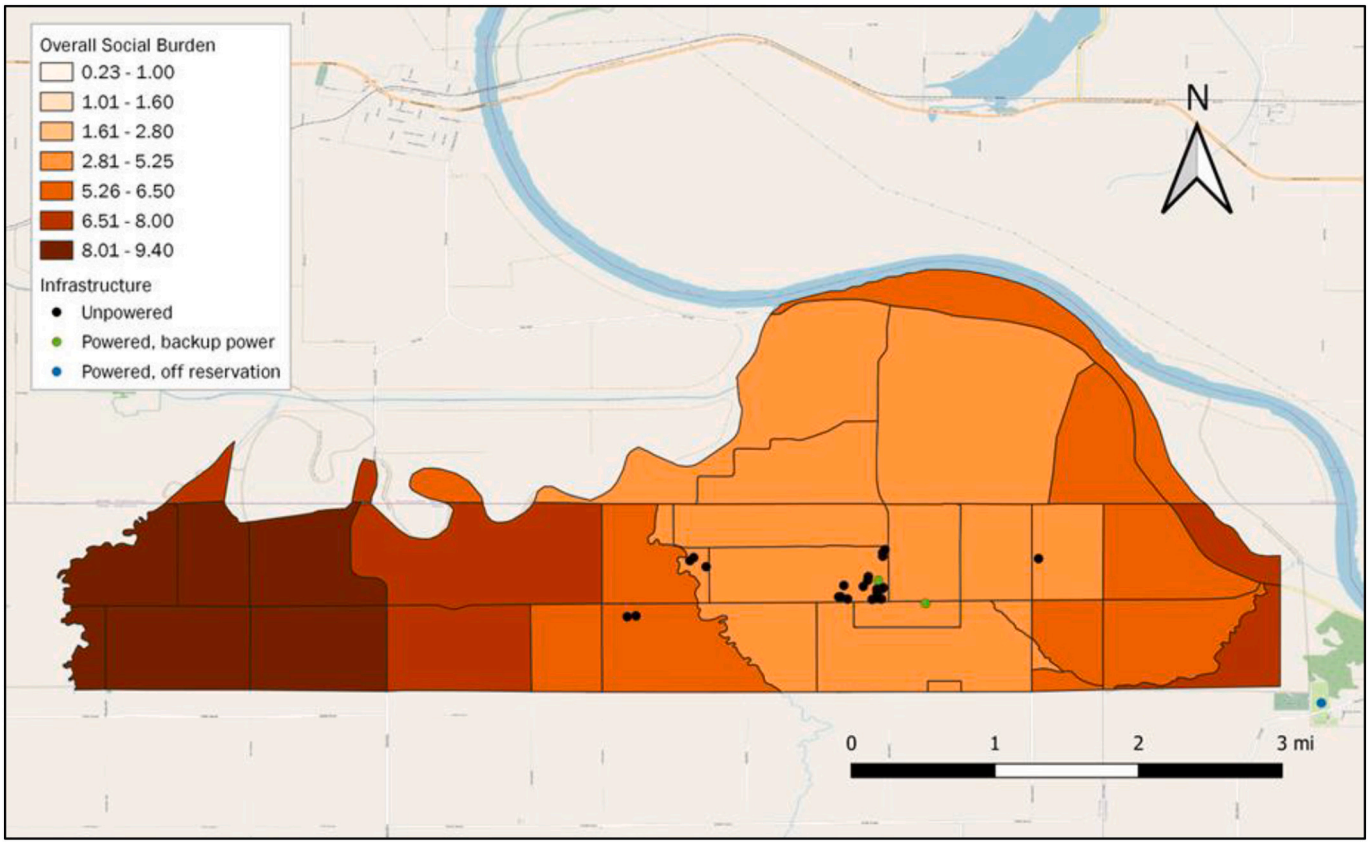

Fig. 3. Per-Capita Social Burden distribution under a "Black-Sky" scenario, during a reservation-wide power outage when only facilities with existing backup generation remain online.

experience has shown the need for resilience valuation metrics that encapsulate not only the financial returns on investment, but that also quantify the other benefits of projects and measure alternatives.

5. Data and methodology

To address this challenge, the ITKN partnered with Sandia National Laboratories and the National Renewable Energy Laboratory to extend techno-economic design optimization with the addition of a framework to quantify the social impact, equity, and resilience value of microgrid alternatives. This enabled the alternative technological solutions (i.e. microgrid designs) to be evaluated not only with respect to their capital and operating costs and power production, but also with respect to their non-economic resilience value.

Facilities on the ITKN reservation include a casino, gas station, daycare center, police department, fire department, a tribally owned and operated medical clinic, administrative offices, wellness center, Boys & Girls Club, and numerous residences. The configuration of existing power infrastructure, the location of reservation facilities, and estimated costs for new construction (e.g., trenching, line development) led the ITKN to consider 5 alternative microgrids to serve these facilities (Fig. 1). The locations of the microgrids were selected to modulate the impact of potential power outages by maintaining continuous service for critical services and buildings on the reservation. Due to the adjacency of facilities considered under scenarios M1-M4, the microgrids were merged into a multi-facility "Casino Cluster Microgrid" design. The Boys & Girls Club and tribal housing complex microgrid (M5) was evaluated separately.

Monthly utility bills were collected from residents and businesses on the reservation, which were then used to evaluate peak power demand and seasonal load changes. The Hybrid Optimization of Multiple Resources (HOMER®) microgrid simulation and optimization tool [36] was used to estimate energy production from ground-mount solar photovoltaic (PV) systems, the proportion of the renewable energy used onsite versus exported to the utility, the amount of energy cycled through the batteries, and the amount of fuel used by existing back-up diesel or propane generators (Table 1). Solar PV arrays were sized so that annual production is roughly equal to the annual consumption of the load being served. Battery storage systems were sized to meet 3–5 h of average load in the event of a blackout. Propane and diesel generators, either existing or new, were modeled to serve the loads during longer outages. Estimated capital, operating costs, and available incentives, such as federal investment tax credits, were used to evaluate project economics and determine the appropriate combination of various investment streams needed to implement these projects.

Social Burden analysis was performed using the Resilient Node Cluster Analysis Tool (ReNCAT, [37]) and the QGIS Social Burden plugin [38]. The Social Burden area of interest (AOI) was bounded by the Iowa Tribe of Kansas and Nebraska reservation boundary. Social Burden scores were calculated only for the population within the AOI. Data describing population characteristics across the AOI was retrieved from the U.S. Census Bureau. In consultation with the ITKN, 2020 Census data on county-level mean income was used as the "attainment factor". The spatial distribution of population was estimated using 2020 Census population counts by census blocks. For numerical purposes, Census blocks with population counts of 0 were assigned a nominal value of 1. Data related to the mapping of critical services and facilities was collected in collaboration with the ITKN. Sandia worked with ITKN to collect and refine a list of critical services relevant to ITKN residents. Then, Sandia worked with ITKN to identify and map on-reservation infrastructure facilities that provide the abovementioned critical services. A limited number of off-reservation facilities known by ITKN to be

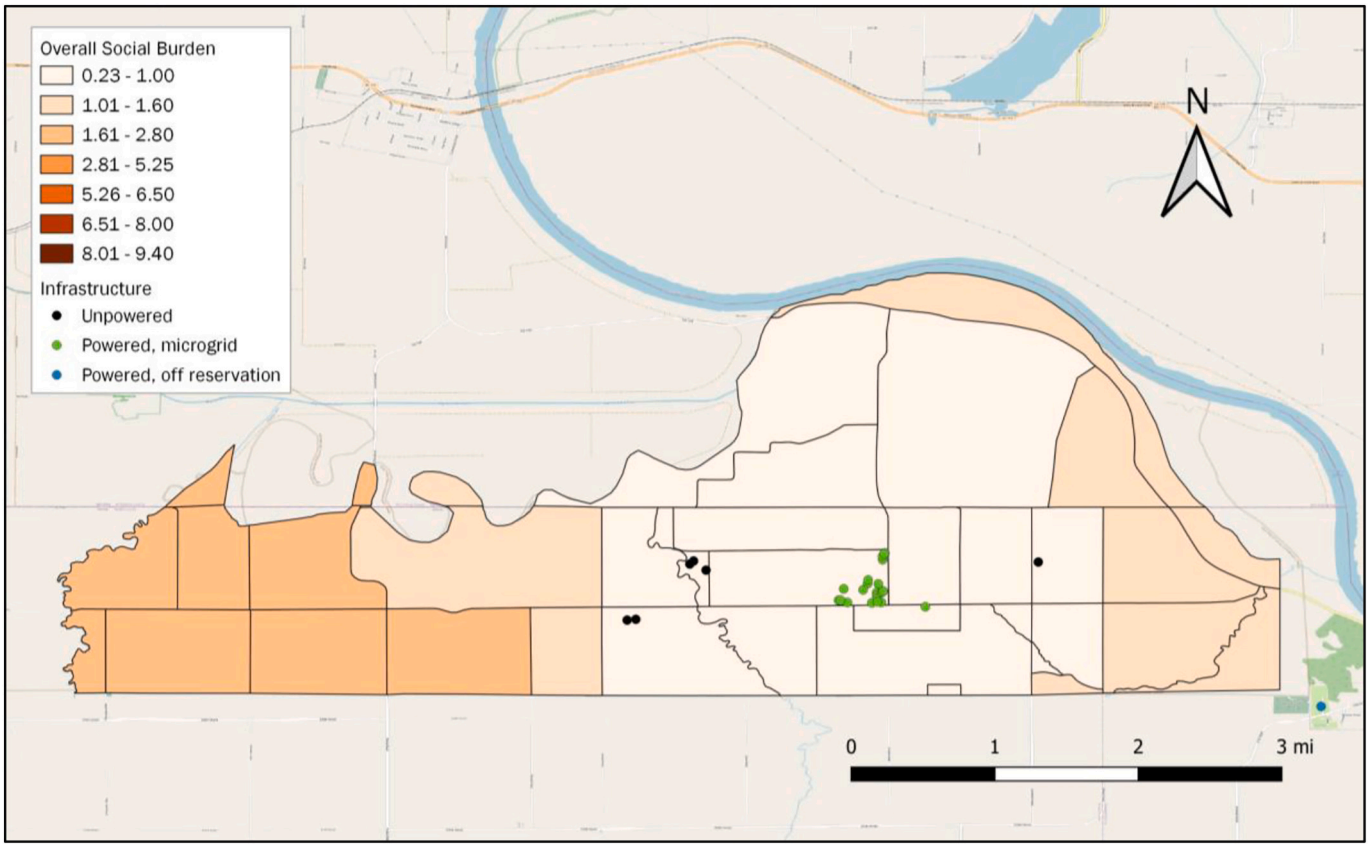

Fig. 4. Per-Capita Social Burden distribution under a "mitigation" scenario, with the inclusion of the hypothetical Casino Cluster (M1-M4) microgrid.

regularly accessed by residents were also included in the analysis. These included 11 cell towers, 2 airports, 2 FM radio transmission towers, 1 hospital, 1 grocery store, and 1 housing facility. ITKN scored, on a scale of 0 to 5, the degree to which each facility provided each one of the critical services to the entire community during regular day-to-day operation. Finally, facilities with backup generators were recorded with input from the ITKN.

To calculate the impact of power outages on Social Burden, and the impact deployment of a microgrid might have on community resilience (vis a vis improved service availability), three power outage scenarios were compared. The first scenario represents "Blue-Sky" conditions. This is the baseline scenario, representing the maximum service availability and lowest possible burden. The second scenario represents "Black-Sky" conditions. This is the worst-case scenario, representing a complete reservation-wide grid outage which is not mitigated by any additional resilience measures other than any currently deployed backup generation. The third and final scenario represents the mitigation scenario. For the purposes of this analysis, this scenario is referred to as the "Microgrid Scenario."

6. Results and discussion

Table 1 presents the results of the HOMER analysis. When evaluating microgrid configurations, ITKN's goals were to ensure that Tribal loads are met during grid power outages, and to maximize onsite renewable energy production. The Casino Cluster microgrid (combining M1-M4) and the Boys & Girls Club and tribal housing complex microgrid (M5) were selected as frontrunners among the five initial microgrid alternative designs (Fig. 1) by the ITKN.

Comparison of Social Burden results by population group, by service type, and by power outage scenario allowed the ITKN to baseline the extent to which infrastructure limitations currently impact community members, to directly measure the dependency of ITKN residents on off-reservation facilities and services, to understand inequities within and outside their community, to measure the impact of power outages on people, and to quantify the resilience value different microgrid configurations would have as the percentage of the Social Burden differential that would be alleviated by the proposed technology investment.

In the "Blue-Sky" scenario, the bulk grid provides power to the entire utility service territory, including the ITKN reservation (Fig. 2). All on-reservation and off-reservation facilities are powered and provide services as usual. The power system introduces no additional burden on top of what exists as a function of infrastructure availability and the population's ability to expand time, resources, and money obtaining critical services. Burden is at its lowest. The per-capita Social Burden distribution under a "Blue-Sky" scenario shows the lowest levels of burden in census blocks located closest to the clustering of on-reservation infrastructure locations in the center of the reservation.

In the "Black Sky" scenario, a hypothetical bulk grid outage interrupts power provision to the ITKN reservation for some extended period of time (Fig. 3). While this is a hypothetical scenario and is event-agnostic, it is consistent with the extent and duration of historic outages that have occurred on the ITKN reservation in the past, and which the ITKN wish to mitigate with the construction of one or more microgrids. All on-reservation facilities, aside from those with independent backup power (i.e., the casino and water production well) are assumed to be left without power and go off-line. Offline facilities do not provide services for the duration of the outage. Facilities with backup power and facilities outside of the reservation are assumed to remain online and continue to provide services as usual. Burden is at its highest, magnifying many of the same disparities observed during the "Blue-Sky" scenario (Fig. 2).

Results of three mitigation scenarios, in which the two composite scenarios are evaluated separately and in combination, are shown in Figs. 4–6. In the final scenario, Social Burden is evaluated with the

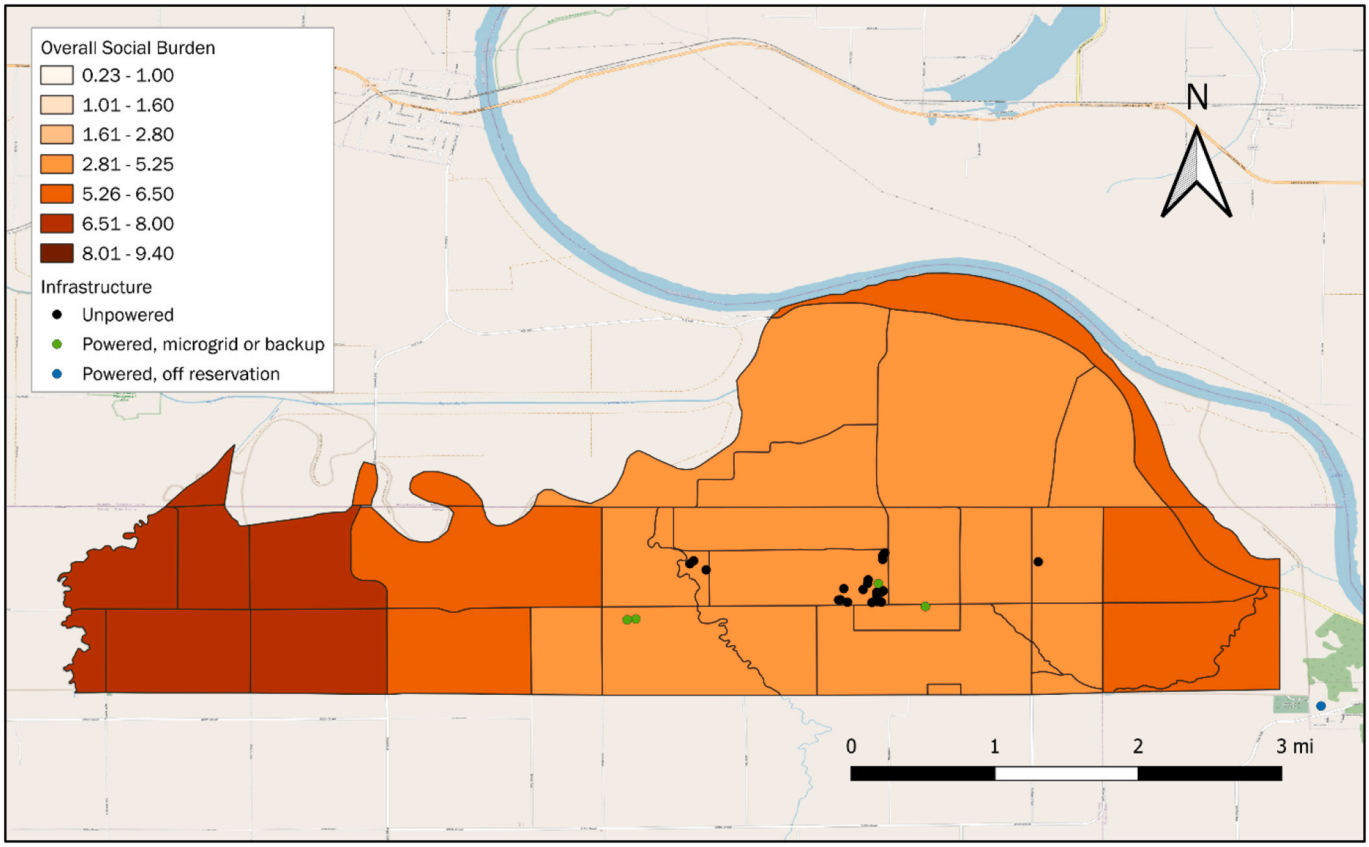

Fig. 5. Per-Capita Social Burden distribution under a "mitigation" scenario, with the inclusion of the hypothetical Boys & Girls Club and tribal housing complex (M5) microgrid.

inclusion of both of these two hypothetical microgrids (Fig. 6). Facilities which are part of M1-M4 and M5 do not lose power, and critical service provision at these locations continues at their "Blue-Sky" baseline levels. All other on-reservation facilities, aside from those with independent backup power are assumed to be left without power and go off-line. Offline facilities do not provide services for the duration of the outage. Facilities with backup power and facilities outside of the reservation are assumed to remain online and continue to provide services as usual. This scenario maps closely to the "Blue Sky" scenario, though the actual burden values are marginally higher, as full power to all facilities is still not achieved.

In Fig. 7, Social Burden scores are shown summed across all service types and population groups. Differences in social burden reductions across these scenarios are the result of differences in the number and type of critical services that are successfully powered by the bulk grid or the hypothetical microgrid designs.

In the case of the ITKN case study, state and utility-level financial incentives (e.g., net energy metering programs) for project investment were limited. The lifetime costs of construction and ownership of the microgrid could not be fully offset or recovered through energy sales. The overall internal rate of return on the project was estimated at −10 %. Multiple common financial metrics (NPV, annualized monetary benefit, IRR) would counter indicate investment in the microgrid on the basis of economic considerations alone.

While the economic viability of energy projects – or any other infrastructure investments – is an important consideration, clean energy microgrids with battery energy storage and back-up generators increase energy resilience, reliability, and Tribal sovereignty for the ITKN. These additional goals are not properly captured by profitability alone. Social Burden analysis was able to demonstrate that not only is there a very significant positive resilience value to the project (such that 94 % of the community impact of power outages could be mitigated by the construction of the proposed microgrid), but also that there are significant, quantifiable negative impacts to continuing to forego or delay the project that can be measured through the increase in Social Burden during an outage unmitigated by any microgrid intervention.

Federal incentives, including rebates, grants, tax credits, and low-interest financing, can help to support cost-effective project development for Tribes in areas with limited state and utility incentive programs. These mechanisms can help to ensure that projects break even or that they do not increase energy costs for consumers. However, communities have historically experienced challenges in securing these types of competitive assistance opportunities, when the only quantitative, widely accepted valuation methodology for describing the value of these resilience projects consisted of profitability indicators. As a result, communities become trapped in a vicious cycle where incentives are required to bridge the profitability gap, but those very incentives reward project profitability. This was the experience of the ITKN as well, until recently, when through the application of equitable resilience valuation (via Social Burden), the ITKN were awarded over $22.5 million in combined grant funding by the U.S. Department of the Interior and the U.S. Department of Environmental Protection Agency to construct the Casino White Cloud (M1) and Boys & Girls Club and Tribal Housing Complex (M5) microgrids, along with workforce development programming on installation, operation, and maintenance [11–13].

We posit that the inclusion of Social Burden addresses a missing portion of community benefit from resilience investments. Fig. 8 explains how Social Burden compliments other commonly used metrics such as profitability and energy burden when considering the dimensions of energy cost, household income, incentives, and service availability. Specifically, Social Burden enables communities and potential investors to understand how critical service availability is

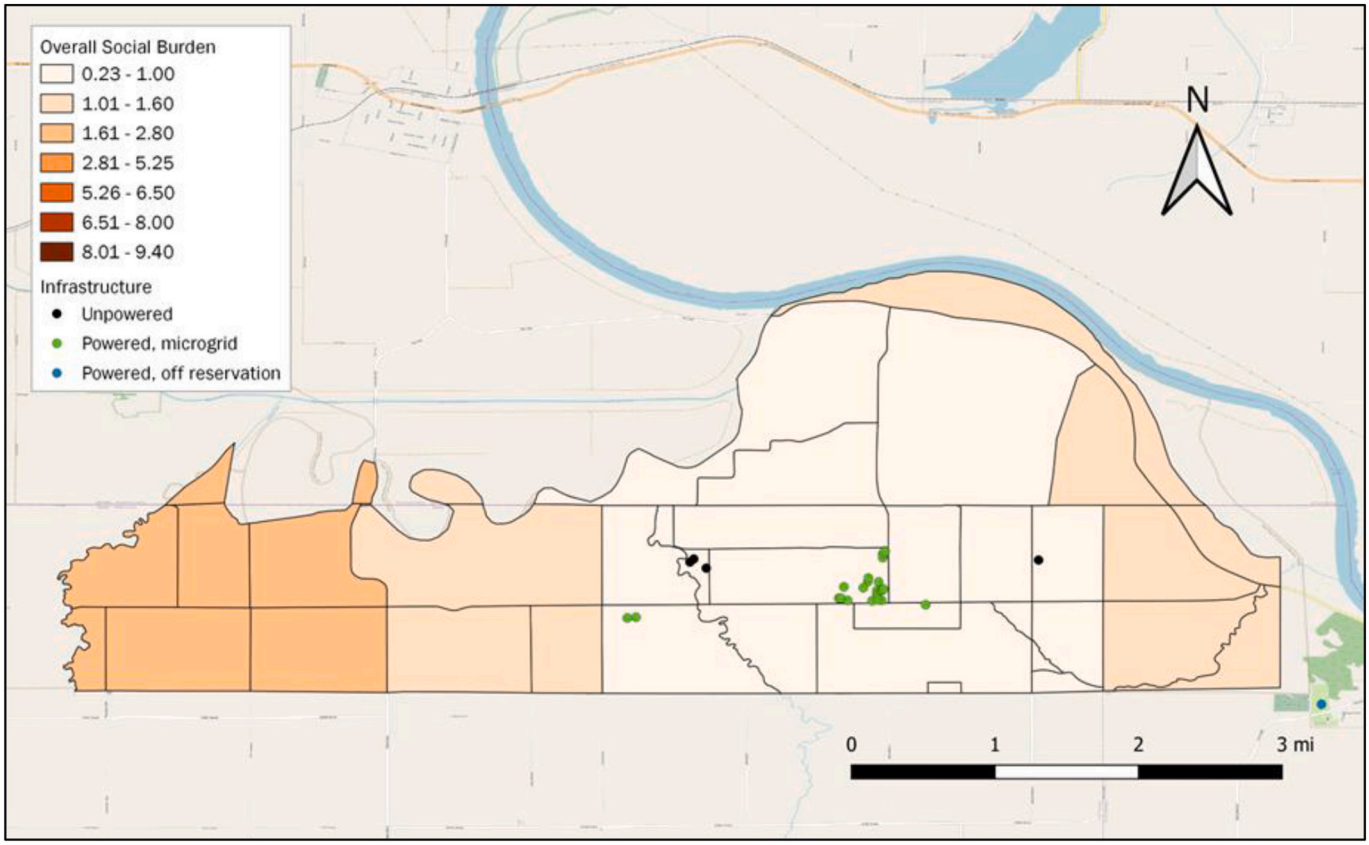

Fig. 6. Per-Capita Social Burden distribution under a "mitigation" scenario, with the inclusion of both the hypothetical Casino Cluster (M1-M4) and the Boys & Girls Club and Tribal housing complex (M5) microgrid designs.

enabled as a function of what infrastructure is/is not powered (which can be affected by resilience investments) in relation to the economic means of community members (which are largely inherent to the demographics of a given community). Each quadrant is shaded from dark orange to green to show the transition from less ideal outcomes to more positive outcomes, respectively. Other communities where Sandia has conducted Social Burden evaluations are included alongside ITKN as additional reference points for illustration purposes, but discussion of results for those communities are outside the scope of this paper. Note that a given community can perform well in one metric while performing poorly in another, which underscores the need for a more holistic view when determining the potential impact of resilience investments.

7. Recommendations for better integrating non-financial benefits into investment decision making

To overcome the present challenges of securing financing for resilience investments, we recommend that Social Burden become embedded as a project evaluation metric in foundations, such that there can be a common, threat-, technology-, project-, cause-, and recipient-agnostic metric that quantitively demonstrates the social benefit (Social Burden reduction) of a given project. Foundational money is uniquely sized to be a good match to small community projects, including small tribal communities. Because foundational awards can be used as cost share, foundational money is an important linchpin that can help projects clear the bar to be viable candidates for federal, or traditional (bank) private financing. This is particularly important for tribal communities pursuing energy sovereignty and establishing TUAs because in these instances, embedding metrics like Social Burden from the top-down in state PUC planning frameworks is less impactful than if these metrics are also used to consider financing.

Communicating the value of resilience to funding partners is an active area of ongoing theoretical and applied research. First, there is a need for metrics, such as Social Burden, to be more widely adapted. Second, there is a critical opportunity, while the field of resilience valuation and its real-world adoption matures, to avoid fragmenting decision-making by creating a convoluted ecosystem of various alternative metrics that cannot be compared [39–41]. ITKN coalition members were trained on the use of Sandia and NREL tools, including the foundations of the methodologies used as well as input data collection and pre-processing, during a week-long hands-on workshop. The workshop employed a "train the trainer" model which was intended to allow the ITKN to integrate these tools into their own future planning efforts as well as to train other Tribal communities in their application.

8. Key limitations and future work

At present, Social Burden can only be applied in a relative manner because thresholds for what would constitute "acceptable" or "unacceptable" levels of burden have not been implemented. It is still possible to use the metric to rank alternative mitigation strategies (e.g., alternative microgrid configurations) with respect to their ability to provide non-economic resilience value. However, future work is required to develop and extensively validate – with diverse stakeholders and communities – a framework by which "acceptable", "high", and "low" Social Burden scores could be identified and "actionable" levels of burden could be established.

Follow-on work is also needed to test and validate methodology by which we can assimilate financial and non-financial (social) costs of resilience events into an integrated evaluation framework. Some models, which monetize avoided social costs, already exist. A leading

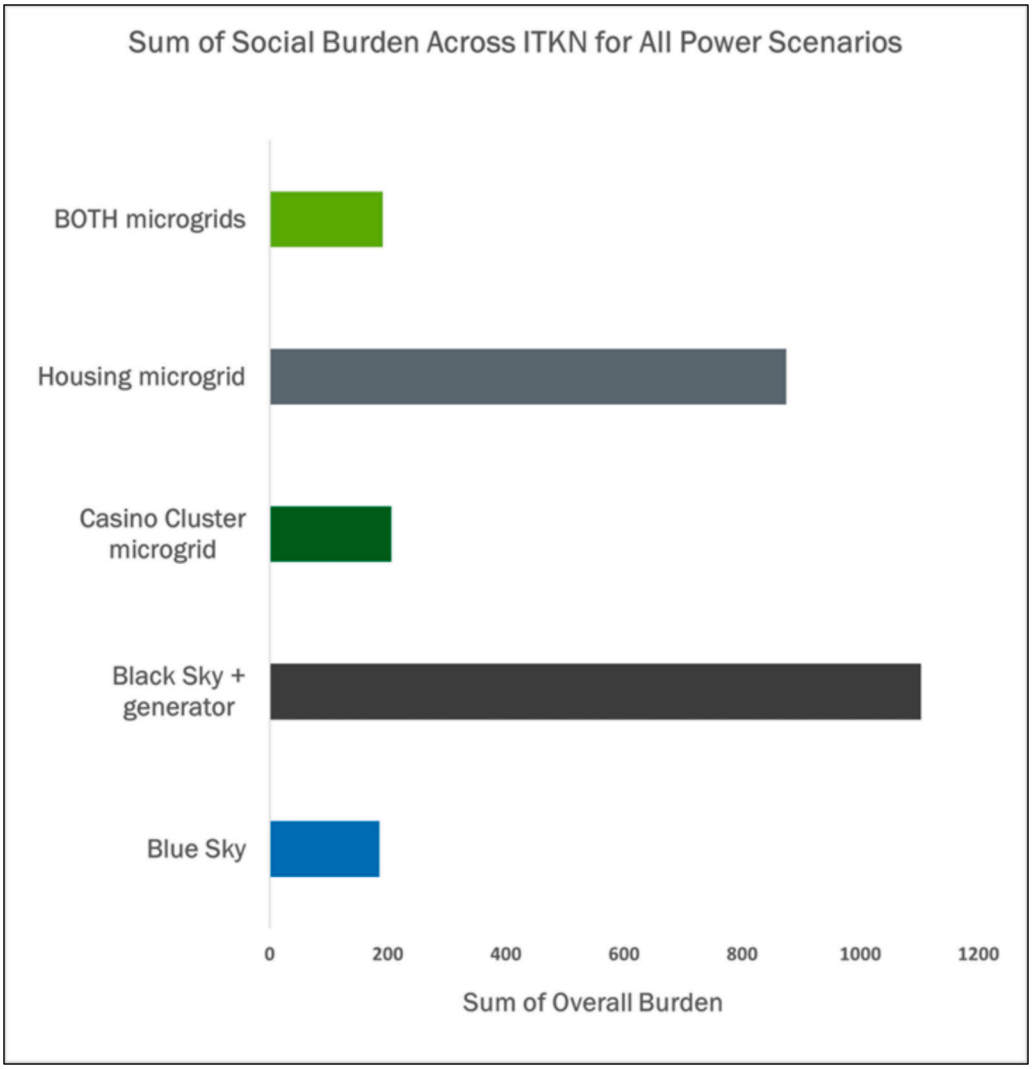

Fig. 7. Comparison of Social Burden across different power scenarios ("Blue Sky", "Black Sky", Casino Cluster microgrid (M1-M4), Boys & Girls Club and tribal housing complex microgrid (M5), and both microgrids (M1-M5)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

example is the FEMA Benefit Cost Ratio (BCR) [42]. The BCR is the net present value of the benefits of a project divided by the costs. While the costs are exclusively financial (e.g. the costs of construction, operation and maintenance, permitting, in-kind contributions), the benefits include a number of non-financial factors whose value is estimated in dollars (e.g., foregone mental stress and anxiety; loss of critical facility service/function). However, the BCR estimates include many simplifications, including equating the cost of critical services (i.e. critical facility annual operating budgets) with their value. The framework that integrates Social Burden with financial costs of resilience events should take into account the non-linear increase in social and economic costs of outages, and consider that in low-resource, low-income communities, outages which industry standards may classify as reliability events because of their duration, may actually have an outsize impact (akin to outages currently classified as 'resilience events') because of the high relative economic burden of the damages or the increasing vulnerability of the population, when comparing them to more affluent, more resourced communities where financial means are higher and alternatives are more readily available and proximate to where people live.

9. Conclusions

In this article, we highlighted a case study performed in collaboration with the Iowa Tribe of Kansas Nebraska in the U.S. However, despite the particularities of Tribal governance, energy systems, or the social and physical infrastructure landscapes more broadly, the overall problem of the valuation of resilience investments is universal for all utilities and communities and largely transcends asset ownership structures. Because resilience investment needs may be infinite and will always need to be approached using limited funds that have to be wisely allocated among multiple objectives such as reliability, service expansion, affordability, and decarbonization, solutions to the need for a valuation framework that has been developed and demonstrated in a tribal context will still be relevant in other types of communities as well.

Sandia scientists are working in communities and with regional regulators across the US to refine and embed these methods into decision-making. The Social Burden metric has been used by over 20 communities at vastly different spatial scales, from several hundred people in the case of the IKTN, to 15 million in the case of work with Southern California Edison and the California Public Utilities Commission [30], and in community types including rural, urban, and in between.

In this specific tribal case study, detailed financial and cash flow analyses were performed to evaluate project economics over time and determine the appropriate combination of various investment streams,

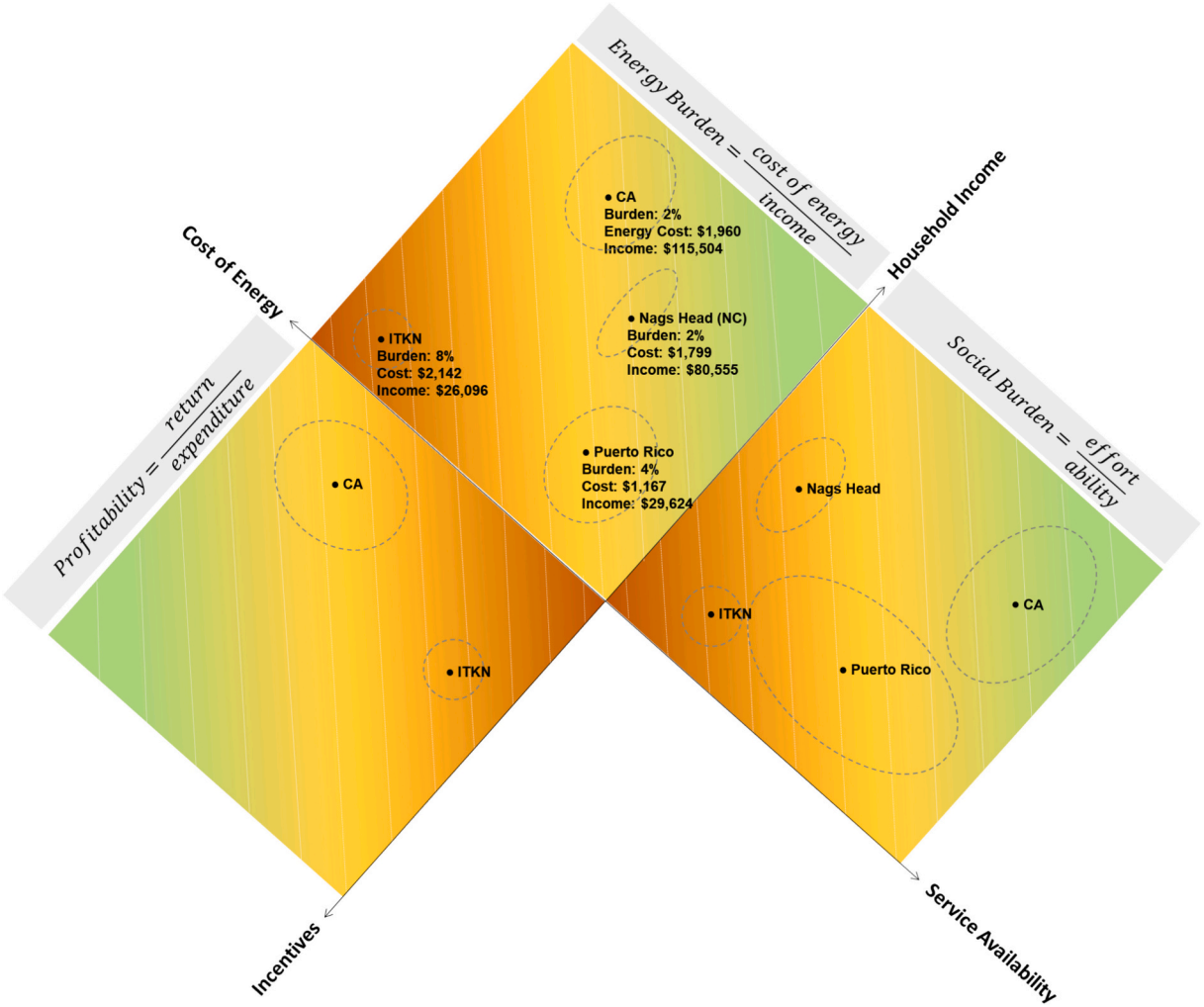

Fig. 8. Schematic representation of the continuum of economic and social impacts associated with the provision of energy. Different communities find themselves at different points along the spectrum of low (red) to high (green) critical service availability, household income, cost of energy, and financial incentives for microgrid and other resilience investments. All these factors combined will determine the financial and social ROI of investments made to provide resilience to bulk grid power outages. It should be noted that for each community, the median value (represented by the centroid point) and the range of individual experiences (represented by the hatched circle), can vary. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

accounting for incentives such as the investment tax credit and potential federal grant resources. The financial modeling indicated that, absent subsidies, the project could not both break even and meet desired renewable energy and resilience metrics. However, the same microgrid project would almost completely mitigate on-reservation power outages, in terms of critical service provision.

With respect to the integration of social and economic valuations, and their concurrent use for project evaluations and investment decision making, we demonstrate how social valuation can help resilience projects break out of gridlock and secure the financing that is required to move from planning to implementation. The approach to include social considerations presented in this case study begins to shift the dialogue toward socially impactful and equitable resilience investments, rather than just profitable ones.

CRediT authorship contribution statement

Olga E. Hart: Writing – original draft, Visualization, Supervision, Project administration, Methodology, Conceptualization. **Amanda Wachtel:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Katherine Jones:** Writing – review & editing, Data curation. **Tony Jimenez:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Peter Gregory:** Writing – review & editing, Validation, Data curation. **David Tam:** Writing – review & editing, Validation, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Olga E. Hart reports financial support was provided by US Department of Energy. Amanda Wachtel reports financial support was provided by US Department of Energy. Katherine Jones reports financial support was provided by US Department of Energy. Tony Jimenez reports financial support was provided by US Department of Energy. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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