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Community energy and socio-technical infrastructure resilience: analysis of mini/micro hydro power projects in Khyber Pakhtunkhwa, Pakistan

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Abstract

In 2014–15, Pakistan's provincial government of Khyber Pakhtunkhwa (KPK) launched a decentralised power generation initiative, installing over 356 small hydro power units to provide electricity to over 2.5 million people in its mountainous regions. This initiative built on the foundation of prior community-based mini/micro hydro-power projects (MHPPs) deployed in the region since the 1980s that have experienced mixed success; by 2020, over 150 units were non-operational. This paper investigates the socio-technical factors influencing the success and failure of these projects, focusing on outcomes and processes integral to community MHPPs. The study analyses the critical implications of MHPPs for socio-economic welfare, gender equity and democratic governance through extensive primary research including field observations at 40 sites, questionnaire surveys with community residents in three in-depth case-studies, and expert interviews with local policymakers and project developers. Analysis shows that electricity provision from MHPPs has had positive outcomes for the communities in terms of improved education, poverty alleviation and economic growth, alongside enhanced access to information and gains in women's entrepreneurship and health. Nonetheless, the study also identifies significant shortcomings in the processes involved in community MHPPs related to inadequate technical assessments, monitoring, and evaluation, as well as challenges arising from undemocratic governance mechanisms and inequitable participation. By teasing out the multiple socio-technical dimensions that shape infrastructure resilience of MHPPs in KPK, this paper contributes to the broader discourse on sustainable community energy projects and informs policy for decentralised energy transitions that ensure democratic alignment and inclusive design.

1. Introduction

Decentralised energy systems have recently emerged as a significant alternative strategy for pursuing electrification in rural communities currently isolated from the electricity grid. Such systems also represent a viable option for sustainable development and poverty alleviation in the many remote areas in developing economies like Pakistan that are still grappling with substantial energy security and development challenges. In Pakistan, about 12 million people still lack basic access to electricity (IEA 2023). While the country predominantly relies on fossil-based thermal energy (62% of total electricity generation), hydropower plays a substantial role by contributing about 26% to the national electricity output (NEPRA 2023). Currently,

hydropower contributes just over 10 000 MW, yet the potential to generate around 64 000 MW remains largely untapped, particularly within Khyber Pakhtunkhwa (KPK), the northern province of Pakistan (PPIB 2022).

Pakistan's national energy strategy (NTDC 2021) targets a significant increase in renewable energy capacity, aiming for 60% of the installed capacity by 2030, with a substantial focus on hydropower sources (Isaad 2022). Although this policy primarily targets large-scale hydropower development, the implementation of mini/micro hydro power projects (MHPPs) represents a crucial step towards realising these goals, not only for enhancing energy access but also for fuelling economic development across the country's most isolated regions. In Pakistan, MHPPs have been in operation since the early 1980s and are seen as a successful localised alternative for electricity access in off-grid communities, particularly in the mountainous regions of KPK, where the geographic and hydrological conditions are favourable for such installations. Studies suggest that by 2015, over 500 MHPPs had been installed in the region (Meier and Ahmad 2019). Aimed to provide cheaper and more reliable electricity to the region, whilst these projects have been instrumental in lighting homes, powering small industries, and improving the community's quality of life, they face significant challenges in their operation, efficacy, and longevity. Field evidence, alongside interviews with local policy bodies and project developers, suggests that ineffective operations and infrastructural limitations have resulted in more than 150 MHPP units[5] reportedly becoming non-operational over the years.

Previous studies show that despite clear advantages, the realisation of decentralised renewable energy projects hinges on their technological and environmental feasibility (Helmrich *et al* 2021, Inam Ullah *et al* 2023), while their long-term sustainability relies on the integration of these systems within local socio-cultural, political, and economic contexts (Duit *et al* 2010, Lorenz 2013, Bahadur and Tanner 2014, Kemausuor *et al* 2018), and requires building a nuanced understanding of local community dynamics (Parish 1999, Thomas *et al* 2019, Kanoi *et al* 2022, Khalid *et al* 2023). Whilst participatory governance as a framework for development is certainly not new (e.g. Cooke and Kothari 2001), the literature on decentralised renewable energy has recently seen a surge in community energy as a new policy tool for sustainable transitions (Seyfang *et al* 2013). Despite the significant potential of localised energy projects like MHPPs, there remains a critical gap in understanding the resilience factors of community energy projects (CEPs), particularly in the global South and in Pakistan.

Of the limited research on MHPPs in Pakistan in recent years, focus has primarily been given to their technical assessment (Khan *et al* 2016, Brown *et al* 2019, Kamran *et al* 2019, PPIB 2022), followed by socio-economic outcomes (Khurshid and Saboor 2013, Luqman *et al* 2013, Ul Rehman *et al* 2023), while far less attention is given to the governance processes that determine their failure or success. Although some studies have focused on social mobilisation (Ahmed *et al* 2009, Azam *et al* 2018), and women's development (Rafi Khan and Rafi Khan 2012, Khan 2015, Ali *et al* 2016), research on project impacts on community dynamics, local economies, and social structures remains limited. Although previous studies emphasise community acceptance and participation (Nadeem and Hameed 2008, Schillebeeckx *et al* 2012, Wolsink 2020, Wahlund and Palm 2022), less attention has been given to examining the diversity in participation (Grossmann and Creamer 2017) and equitable distributions in *outcomes* and *processes* (Walker and Devine-Wright 2008). Realising the potential of MHPPs as CEPs requires a nuanced socio-technical approach that encompasses strategic alignment with existing social structures, and a justice-based approach to community benefits, needs and governance models that enhance democratic, inclusive, and participatory practices.

This paper aims to provide a comprehensive assessment of the infrastructure resilience of MHPPs as complex socio-technical systems. Through extensive mixed-methods field research, the study builds an in-depth analysis of factors influencing the successes and failures of these CEPs. Further, it provides key policy implications for building resilient and equitable community energy systems that can withstand socio-economic shocks and stresses while aligning with the future aspirations of local populations, offering key insights for the future of decentralised energy projects in Pakistan and similar contexts globally.

[5] This number was quoted by PEDO and Hydrolink Engineering & Equipment Company Pvt Ltd during consultations with the authors. However, lack of any official documentation on non-operational MHPPs to date makes it difficult to verify exact numbers. Nonetheless, a review of previous literature provides some evidence to support this claim. For example, Maier's (2007) detailed investigation of micro hydels built by AKSRP in Chitral showed that around 30 had been abandoned at the time. A 2018 assessment by GIZ (Farid 2018) also showed that about three-quarters of the examined plants showed technical faults, while 18% were non-operational. Further, an external assessment of PEDOs power plan in 2021 (Adam Smith International and Bridge Factor 2021) showed that of the 356 MHPs planned, 107 were non-operational, of which 56 had failed due to lack of communal capacity and increased technical complexity that made community level O&M non-feasible. Pakistan government's yearly audit reports for KPK continue to report on PEDO's lack of proper management and documentation for MHPPs.

2. Literature review

2.1. Community energy and socio-technical infrastructure resilience

Community energy projects broadly describe localised, small-scale and/or decentralised energy initiatives that involve some form of community engagement or participation (Bauwens *et al* 2022). These projects facilitate the development of sustainable energy technologies and practices, producing local benefits by setting goals that may be social, economic, environmental, political or infrastructural in nature (Walker and Devine-Wright 2008, Bauwens and Devine-Wright 2018). Within the engineering and environment literature, energy infrastructures has been depicted as comprising both physical networks and governing institutions, both equally crucial to the system's adaptability and transformational capacity (Helmrich *et al* 2021). Echoing urban studies literature which characterises infrastructure as both socio-political and technical-material (e.g. Graham and Marvin 2001, Graham and McFarlane 2015), this perspective represents infrastructural development as deeply intertwined with social processes, governance structures, and economic systems, all influencing the organisation and operation of energy projects. Aligned with these arguments, in this paper we conceptualise CEP infrastructures as complex socio-technical systems that involve dynamic interaction between technology, community, and the various local and regional organisations involved in funding, governance, and operation.

The sustainability of CEP infrastructures hinges on their resilience—specifically, their capacity to anticipate, prepare for, respond to, and recover from disruptions (Helmrich *et al* 2021). Whilst resilience has traditionally been linked to technical systems in engineering studies, more recent scholarship (Thomas *et al* 2019) integrates it with human resilience, recognising it as essential to infrastructure resilience. These studies show how humans and social systems interact with technological systems through dynamic processes to overcome vulnerabilities and facilitate favorable outcomes, such as climate adaptation and disaster management (Park *et al* 2013). This understanding of resilience has been extended within the social sciences (Lorenz 2013) to the interplay between social and ecological systems, emphasising their adaptive, coping and participative capacities as critical for sustainability and absorption of disturbances. Socio-technical understandings of resilience, including those for infrastructure, have also been linked to empowerment (Fischer and McKee 2017). Others (Ruth and Goessling-Reisemann 2019) similarly articulate resilience as a systemic attribute influenced by both critical technological systems and the institutions that govern them. This view considers resilience as extending beyond a system's absorptive and adaptive capacities to include learning and self-regulating capabilities, crucial for transformative action. This multifaceted conceptualisation of resilience, incorporating social, ecological, and technological aspects, is critical to understand and enhance the resilience of CEP infrastructures as socio-technical systems.

Despite the socio-economic benefits of CEPs highlighted in literature (e.g. Walker and Devine-Wright 2008, Seyfang *et al* 2013), they can also face significant socio-technical barriers to their resilience. Financial challenges, including secure initial capital investment and sustainable funding, are frequently cited (Rogers *et al* 2008). Regulatory hurdles, complex technological and institutional policies also impede the development and integration of these projects into the wider energy network (Brummer 2018). A lack of technical expertise in communities can further hinder the planning, implementation, and maintenance of energy systems (Yadoo and Cruickshank 2012). Moreover, issues such as energy poverty, the need for energy democracy, and business model adaptation are crucial (Koirala *et al* 2016). Bauwens *et al* (2022) note a shift in community energy initiatives from focusing on transformative, bottom-up participation to prioritising economic over socio-political goals, potentially compromising the resilience of CEP infrastructures. Procedural shortfalls in CEP implementation can impede their effectiveness, failing to deliver economic benefits to *all* community members, which may lead to discontent and reduced participation (Van Der Horst 2008).

Whilst community participation can take various forms in CEPs, Walker and Devine-Wright (2008) identify two core attributes of 'ideal' CEPs: a focus on *outcomes*, i.e. who the project is for, referring to the social and spatial distribution of benefits from the energy project; and a focus on *process*, i.e. who the project is developed and run by, referring to the involvement and influence of a community of people in decision-making. In doing so, the authors emphasise the social arrangements through which energy technologies and systems are implemented and used. Aligned with this view, Yadoo and Cruickshank (2010) contend that the success of rural CEPs hinges on their support for local development and effective economic outcomes, coupled with *democratic* operations (e.g. a 'one member, one vote' policy) to ensure transparency and accountability. However, they also warn of the potential for co-option and coercion by local elites, which could undermine the democratic integrity of these projects. Moreover, studies (e.g. Moroni *et al* 2019) also caution against a one-size-fits-all policy due to wide variations and complexities associated with energy communities, emphasising the need for appropriating to local circumstances and contexts. Yadoo and Cruickshank (2010) further highlight the need for appropriate scaling in CEPs. Projects that are too large

may face communication and infrastructure challenges, while those that are too small may fail to meet community's energy requirements, jeopardising financial stability and resilience.

CEPs in the global South are often part of rural electrification and have been used in participatory development as a more sustainable model for decades (Cooke and Kothari 2001). Despite improving energy access, these initiatives frequently encounter situated challenges like higher logistical costs, maintenance issues, and difficulties in technology adaptation (Mirza *et al* 2009, Bhattacharyya 2013) and socio-cultural acceptance (Subedi *et al* 2023). Linked to this are concerns for energy justice (Walker and Day 2012). Previous studies (e.g. Monyei *et al* 2018) show that while many developing countries have seen widespread dissemination of small-scale rural electrification projects, these have not always resulted in systematic rural empowerment and poverty alleviation. Rather, CEPs act as microcosms of larger society, and represent socio-technical processes that can reproduce existing system and societal inequalities (Castán Broto and Neves Alves 2018), such as gendered inequalities (Grünenfelder 2013, Khalid and Foulds 2021). A justice-based approach (Walker and Day 2012) in CEPs thus entails fair access and distribution of energy-related benefits, recognition for the diverse needs, objectives and aspirations of community members, specifically marginalised groups, and procedural justice that ensures equitable representation and participation in governance and decision-making.

2.2. Hydropower and CEPs in Pakistan

In Pakistan, whilst the development of hydropower energy dates back to the 1920s (Sibtain *et al* 2021), the construction of small off-grid hydro units for villages has been in operation since the mid-1970s under the former Council of Appropriate Technology (PCAT), as part of the Ministry of Science and Technology. By early 1983, PCAT had installed almost 40 plants, with outputs in the range of 5–1.5 kW, in the remote villages of northern Pakistan (Foley 1992). These early projects laid the groundwork for more structured programs in the decades to follow. Pakistan's Rural Support Programmes Network, including the forerunning Aga Khan Rural Support Programme (AKRSP), has been a pivotal player, launching its micro-hydro power program in northern Pakistan in the early 1980s. By the mid-2000s, AKRSP had facilitated the installation of over 150 micro-hydro plants, significantly impacting rural electrification in regions like Chitral (Maier 2007).

The development and management of decentralised micro-hydro projects in Pakistan involve multiple stakeholders including local government bodies, NGOs, international donors, and community organisations (World Bank 2002). These stakeholder are crucial in project funding, design and implementation (Maier 2007), with many projects relying on a community management model described by Ahmed *et al* (2009) as a 'production model'. This model serves as both a purpose and a unifying force for the community organisation. International development agencies like AKRSP and local NGOs like the Sarhad Rural Support Programme (SRSP)[6] provide technical and financial support, while the community (e.g. through village organisations (VOs), women organisations (WOs) or other local support organisations (LSOs) at the union council level) contributes initial resources, including land, labour, time and local materials to cover about 20% of project costs, and later manages operation and maintenance (O&M) (Maier 2007). Recently, with governance reforms (Elahi *et al* 2015), the KPK government taken a more active role in initiating MHPPs, with funding from international donors like the Asian Development Bank, although management continues under the participatory development model by RSPs.

Despite the vast potential and relative success of many MHPPs in Pakistan, evidence shows that not all such projects have been successful. A critical appraisal reveals that their sustainability and expansion has faced several infrastructural challenges (Ahmed *et al* 2009). Technical challenges include the inadequacy of local physical networks, such as access roads for transporting machinery and materials to remote project sites, impacting project cost and complexity (Sibtain *et al* 2021). Variability of regional water flow poses another challenge, affecting reliability and output (Uddin *et al* 2019). A World Bank report (2002) also raised sustainability concerns regarding the maintenance capacity for micro-hydel infrastructures. Donor dependency, complexities in engaging diverse community groups, and limitations in government capacity all present critical institutional issues that impact project success (Settle 2012). Additionally, the lack of local expertise in designing and maintaining MHPPs results in inefficiencies and increased operational costs (Uddin *et al* 2019). Further, there is a notable deficiency in supportive policies tailored for small-scale renewable projects like MHPPs, as Pakistan's national energy strategy has traditionally favoured large-scale hydroelectric and fossil fuel projects (Isaad 2022, NEPRA 2023), with regulatory authorities slow in introducing tailored feed-in tariffs for small-scale projects, hampering the growth of MHPPs (NEPRA 2023). Frequent policy changes, lack of coordination and absence of clear guidelines hinder investment and complicate compliance for project developers (Uddin *et al* 2019, Isaad 2022). Although the country's

[6] The Sarhad Rural Support Programme (SRSP) is part of the Rural Support Programmes Network (RSPN), which comprises 12 Rural Support Programmes.

Alternative and Renewable Energy Policy supports the development of small hydro projects up to 50 MW, it fails to address significant implementation challenges including inconsistencies with national grid expansion, market competition, and financial barriers (Ullah *et al* 2019). Similar policy challenges impeding the mainstreaming of off-grid hydropower development are also evident in other regional countries (Hussain *et al* 2019), although there are successful examples where comprehensive policies and supportive measures—such as government subsidies, harmonised policies, tariff setting, bilateral support, and effective grid integration—have facilitated the success of small-scale energy projects (Sovacool and Drupady 2016).

Previous studies show that social acceptance and community involvement are critical to the success of MHPPs, yet they also present significant challenges. A study of MHPPs in Pakistan shows that social resistance often stems from conflicts between upstream and downstream communities over water resource allocation (Uddin *et al* 2019). In an extensive study on governance mechanisms of MHPPs in Chitral, Maier (2007) demonstrates that projects can face resistance from local communities due to a lack of engagement, personal disputes, or perceived inequalities in the distribution of benefits. However, emphasis is also given to the key role such systems can play in advancing decentralised electrification efforts in rural areas, offering a sustainable and scalable solution to energy access, provided that sufficient efforts are made to improve policy frameworks and community-centric approaches to realise the full potential of MHPPs.

Alternatively, some studies have questioned the RSP's participatory development model in its over-emphasis on technical aspects, neglecting issues of power (Elahi *et al* 2015), and the sectarian and socio-political dimensions that equally influence its success (Cooke and Kothari 2001, Settle 2012). Political instability in northern Pakistan is shown to have significantly hindered the growth of MHPPs (Isaad 2022). Since independence in 1947, continued disputes between India and Pakistan over the larger conflict-ridden region of Jammu and Kashmir has resulted in militarisation, prolonged conflicts, extremism, and underdevelopment in the northern region (Hunzai 2013). As a frontier province with proximity to Afghanistan and the Central Asian republics, KPK has faced an influx of refugees from Afghanistan since the 1980s, along with militant activities, particularly the rise of the Taliban movement in 1995, deteriorating regional peace and impacting socio-economic structures. KPK's struggle for greater autonomy and recognition of the Pashtun identity also led to significant political mobilisation, particularly since the merger of the Pukhtoon Swat state with KPK in 1969 (Elahi *et al* 2015). Sectarian violence, particularly between Sunni and Shia communities, has escalated since the 1980s (Hunzai 2013, Varley 2015). Development projects, including those backed by AKSRP, have often been met with suspicion by local Shia and Sunni groups (Settle 2012). The 2006–10 militancy conflict and flood disaster, alongside internal displacements and rising religious extremism post 9/11 further compounded the region's politico-economic instability (Hunzai 2013, Elahi *et al* 2015, Khalid *et al* 2022), obstructing significant developmental progress.

With regard to CEPs, earlier assessments in the region also highlighted issues of unfairness in human resource policies, accountability limitations, and women's under-representation (World Bank 2002). Equity issues have also diminished engagement and benefits to the poorest communities (Ahmed *et al* 2009). Moreover, projects that focus primarily on techno-material aspects without considering social dimensions often fail to achieve comprehensive success in infrastructure resilience. For example, Holmlund and Rao's (2021) discussion on community-driven development shows that whilst technocratic approaches have proven effective in improving the quality of physical infrastructure, they fall short in improving service delivery, economic welfare, governance and social cohesion. This lack of outright success is particularly true for regions facing fragility and conflict, where participative development has not proven to lead to more inclusive or democratic institutions. Varley (2015) argues that public infrastructures in northern Pakistan act as sites of political and sectarian privilege and exclusion, exemplifying spatially and symbolically the institutionalisation of sectarian differences and furthering political conflict. Other studies (Foley 1992, Maier 2007) also emphasise the significance of institutional processes over mere technical solutions in the success of rural electrification efforts in developing contexts. These insights collectively underscore the need for CEPs to adopt a comprehensive socio-technical approach to truly achieve infrastructure resilience.

To date, a critical contemporary socio-technical review of MHPPs in Pakistan remains limited, particularly from an infrastructure resilience and justice-based perspective. This is despite the substantial evidence which suggests that merely providing access to energy does not ensure significant social benefits and long-term resilience from electrification (Purwanto and Afifah 2016, Saim and Khan 2021, Khalid *et al* 2023). Instead, meaningful outcomes emerge when electrification systems are effectively integrated into the local social, cultural, political and economic fabric at various organisational and decision-making levels (Kaygusuz 2011). Further, whilst the distribution of community benefits through local energy projects is crucial, this addresses only one dimension of the meaning of community, serving to promote a narrower, *outcome-based* rather than *process-based* understanding of community energy (Walker and Devine-Wright 2008). Hence, what is required is an in-depth outcome- and process-based analysis of MHPPs, which this study sets out to provide, to inform socio-technical infrastructure resilience for CEPs in Pakistan.

Table 1. Project phases and overview of data collection.

Phase 1	Field investigation sites	Operational sites:	Non-operational sites
1. Fieldwork—500 household questionnaire surveys	District Swat—5 sites	4	1
	District Mardan—2 sites	2	—
	District Upper Dir—12 sites	11	1
	Chitral Valley—13 sites	8	5
	District Charsada—4 sites	2	2
	District Abbottabad—4 sites	2	2
2. Interviews with professional stakeholders	Stakeholder type	Respondents (men)	Respondents (women)
	Major government department	03	01
	Energy Development Agency	08	01
	Regional Energy Institute	01	—
	Local NGO and Implementing Partner of MHP projects	02	—
	International development agency and Implementing Partner of MHP projects	01	01
Phase 2 Case-studies	Case-study sites	Questionnaire surveys (Total 350 households)	Consumer-base
1.	Jungle Inn MHPP Kalam (400 kW capacity)	128	Commercial centre serving mostly commercial consumers
2.	Ashoran MHPP Kalam (1.2 MW capacity)	122	Predominantly domestic consumer
3.	Ayun MHPP Chitral (700 kW capacity)	100	Predominantly domestic consumer

3. Methodology

Data collection for the study included a mixed-methods approach, conducted in two phases. Phase 1 (table 1) included field observations from 40 MHPP locations in six different districts of KPK. These sites were selected to represent a range of different energy provisioning including off-grid and combined MHP and grid-connected electricity, and included both successful and unsuccessful projects. This first phase involved detailed analysis of the MHPP sites, field observations through multiple visits and questionnaire surveys with local community members. In addition, semi-structured interviews were conducted with policymakers from the KPK government and various stakeholders from local energy companies and international development agencies to better understand the broader policy and energy landscape. The Phase 1 questionnaire surveys, conducted with over 500 households from the local communities across the 40 MHPP sites during October–November 2021, comprised a range of questions pertaining to the technical details of the MHPPs and households' experience and satisfaction with electricity provision. However, the results and analysis of Phase 1 surveys do not form part of the present paper, which focuses mainly on presenting the results from Phase 2.

Phase 2 (table 1), drawing on the preliminary findings from Phase 1, focused on an in-depth analysis from three case-studies, including Ashoran MHPP in Kalam, Jungle Inn MHPP in Kalam, and Ayun MHPP in Chitral. The selection of Chitral and Swat as case-study sites was driven by the government and development sector's concerted efforts on MHP development in these regions, coupled with the availability of extensive prior research (e.g. Maier 2007, Ahmad *et al* 2016, Meier and Ahmad 2019, AKRSP 2020, Khalid *et al* 2022), facilitating a more detailed analysis. The MHPP cases were purposively selected as successful examples from PEDO's 356 MHP project more recently developed. The selection criteria included MHPPs of a size sufficient to be classified as 'mini' (explained below) and each capable of powering over 1000 households.

This second phase, conducted in December 2021-Feburary 2022, included questionnaire surveys with 350 households across the three case-study sites using a stratified random sampling technique. Surveys were conducted with the heads of joint families, often representing more than 10 individuals within the same living space. Questions focused on the governance aspects of MHPPs, in addition to women's use of

Figure 1. Map of Northern KPK showing locations of three case-study MHPPs (Source of images- author).

electricity and participation in community organisation. This paper mainly presents the results from surveys conducted in Phase 2 at the three case-study sites, corroborated by evidence from Phase 1. All research work was conducted with ethical approval from the University of Engineering and Technology, Peshawar. Data collection for questionnaire surveys and interviews followed standard considerations for participants' informed consent, anonymity and secure data storage. Interview quotations utilised in this paper have anonymised interviewee identifiers for gender and stakeholder type.

3.1. Case-study MHPPs

The Jungle Inn and Ashoran MHPP are both installed in Kalam, a northern mountainous region of Swat valley in KPK with a total population of about 22 000 (figure 1). Kalam valley has an abundance of water streams and natural lakes marking its potential for electricity generation through hydro-powered turbines. The Ayun MHPP is in Chitral valley, the mountainous northernmost district of KPK. Located on the Chitral River, the city has a total population of about 50 000 and has numerous sites for harnessing water power, and has historically had the most schemes and highest micro hydel concentration in the world (World Bank 2002).

These MHPP installations were part of a 2014–15 project undertaken by the Pakhtunkhwa Energy Development Organisation (PEDO)- a statutory body responsible for energy and power development under the provincial KPK government. With financial support from the international development sector, PEDO initiated the installation of 356 MHPs in 12 hydel-power potential districts of KPK that have historically been deprived of electricity. This first stage of the project was completed in 2018, providing an estimated number of 104 000 households with electricity. The second stage was initiated in 2022, with a planned total of 1028 MHPs providing 87.82 MW electricity to an estimated 159 000 households. For project operations, PEDO enlisted the support of several NGOs, mainly Rural Support Programmes (RSPs) (including SRSP), based on their established presence and operational strengths within specific regions and districts. As implementing partners, these organisations were entrusted with the task of utilising the allocated funds to develop and integrate projects within the community, along with carrying out feasibility studies. The operational model adopted for these projects followed a build-operate-transfer (BOT) framework, wherein the RSP partner constructs the project, manages it for a designated period, and subsequently transfers ownership to the local community, so as to ensure sustainability and community ownership post-transfer (SRSP 2015).

Before the implementation of MHPPs in the case-study areas, electricity was being supplied to these regions through the Federal Government owned Peshawar Electric Supply Company (PESCO). However, as in many rural areas, this centralised grid system was found to be severely lacking, with electricity supplied for only a few hours daily, greatly affecting the local resident's everyday practices. As such, the local population either relied on fuelwood or petrol-based back-up generators, depending on individual household affordability. The MHPP installations have somewhat compensated for the power shortage and restored electric power in the region.

The three MHPPs (figure 1) were all operationalised with the support of SRSP- the largest non-government organisation supporting renewable, clean, and sustainable energy in Pakistan (SRSP 2015). Whilst the Ashoran MHPP has a predominantly domestic consumer base, the Jungle Inn MHPP is located close to the commercial centre and so serves mostly commercial consumers. Based on the size of the project, the hydro power plants are either categorised as micro, ranging from 5 to 150 kW or mini, ranging from 150 to 1000 kW. The three successful case-studies are thus all mini hydropower projects. The Jungle Inn MHPP is usually utilised to meet the higher summer demand, whereas the Ashoran MHPP is operational during both summer and winter. Together, the two MHPPs provide electricity to 2086 Households, 20 hotels, 10 tailors and a medical facility. The Ayun MHPP serves 1350 households, 150 shops, three government schools, one bank, three mosques and a hospital. All three MHPPs had been installed on natural streams. At all sites, metered connections have been installed to facilitate accurate and efficient billing, and a tariff structure is in place for domestic and commercial consumers, reflecting a tiered pricing strategy designed to effectively manage energy consumption.

The study has several limitations. Firstly, the survey primarily captures residents' perceptions of energy-use and benefits rather than concrete data on, for example, electricity consumption and fuel use, as the sites lacked tools like smart metering for precise household energy measurement. Nevertheless, data on average monthly electricity billing and other fuel-use expenditures were collected. Additionally, the survey responses were predominantly provided by household heads, and since men represented household heads in all joint family households, this limited direct input from women household members due to socio-cultural constraints and the fact that all enumerators were men. Similarly, for the professional stakeholder interviews, the majority of participants were men (table 1). Although effort was made to include women representatives, achieving a gender balance was challenging due to the predominance of men in key roles within the energy sector. Moreover, as this is not a longitudinal study, the authors had to rely on cross-sectional data, preventing a thorough before-and-after analysis on socio-economic impact. This reliance on observations and anecdotal evidence, rather than longitudinal data, makes it challenging to establish clear causal relationships between MHPP interventions and their impacts, a difficulty echoed in previous research (Maier 2007, Ahmed *et al* 2009). For the non-operational MHPPs, findings were largely derived from site observations, informal conversations, and interviews with professional stakeholders. However, there was a notable absence of detailed audits or documented assessments explaining the failures of these MHPPs, further complicating the evaluation of these projects. Where possible, findings were corroborated with previous literature to overcome some of these limitations. However, more detailed longitudinal research and project assessments are needed to accurately determine the factors of infrastructure resilience.

4. Findings

Field observations and analysis revealed considerable variations in the implementation of MHPPs, influenced not only by diverse social and territorial conditions, but also the range of stakeholders involved. Data collection indicated that MHPP systems managed by local NGOs, such as SRSP, were well-structured and better designed with appropriate mechanisms for voltage and frequency control. In contrast, privately owned MHPPs were frequently found to be in poor condition and lacking dedicated powerhouse buildings. Further, there was also some evidence of correlations between size of the projects and their relative success. This is partly because contrary to mini hydro plants, the micro hydro projects often face technical issues resulting from damage to the smaller turbines and less effective control mechanisms in the form of electric load controllers. In addition, their reduced electricity provision is insufficient to meet community needs, particularly for enhanced economic opportunities, resulting in less community satisfaction and long-term reliance, as highlighted in previous studies (Yadoo and Cruickshank 2010). A key factor in the success of the three case-study MHPPs was there relatively larger size which allowed for better electricity provision to meet the communities' diverse needs.

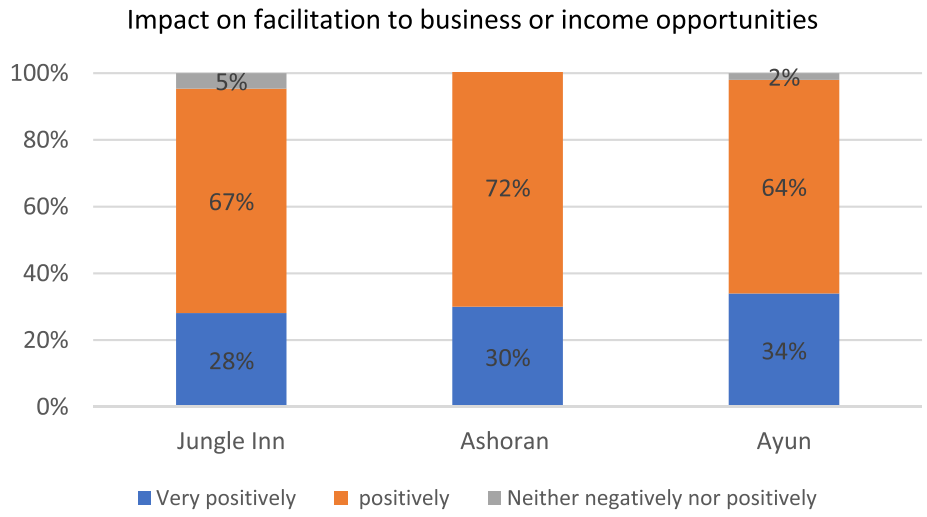

Figure 2. Survey results showing response to impact on facilitation to business or income opportunities.

In the following sections, findings from the Phase 2 household surveys are presented in terms of the outcomes of and processes undertaken in the MHPP case-studies. Where possible, these results are contextualised with field observations and stakeholder interviews from Phase 1.

4.1. Community MHPP outcomes: socio-economic and gendered impacts

Data analysis shows that the implementation of MHPPs in KPK has positively facilitated local economies by providing more reliable electricity to the case-study areas, which has, in turn, supported small businesses and agricultural practices, providing enhanced income opportunities for the village, as positively perceived by most respondents (figure 2).

Most respondents agreed that reliable electricity provision had contributed to poverty alleviation in their households (figure 3). This is because, similar to previous studies (World Bank 2002, SEBCON 2016, Siraj and Khan 2019), reliable power supply has led to increased agricultural productivity, and improved preservation of food products- critical in reducing food scarcity and boosting local income. The community's enhanced economic outcomes result from multiple factors. A critical benefit observed from the introduction of MHPPs is the substantial reduction in household energy expenditures. This is demonstrated in figures 4 and 5, which show household energy spending before and after MHPP implementation, respectively, illustrating a marked improvement in financial savings on energy bills post-MHPP installation. Prior to MHPPs, many households were allocating 25%–45% of their monthly income to energy-related expenses. However, with the availability of MHPP-generated electricity, these expenditures have predominantly fallen below the 25% threshold. This reduction is largely attributed to the shift from using wood and biomass for water and space heating to using electricity, which is not only more cost-effective but also healthier, further resulting in a cut-down of respiratory issues and medical expenses. SRSP evaluates that MHPP projects have improved vegetation and reduced carbon emissions, estimating a reduction of 66 000 tonnes of CO_2 per year since 2016 (SRSP 2015), while also saving the community economic costs of fossil-fuel consumption.

The case of Jungle Inn MHPP is particularly important for energy-related economic benefits. This MHPP primarily supplies electricity to local businesses and hotels, which previously relied on generators or ceased operations after sunset. The availability of electricity has extended business hours and enhanced comfort in hotels, markedly boosting their stability and growth. In the hospitality sector, tourism from major urban centres in Pakistan has surged due to improved access to electricity, allowing hotels to remain operational throughout the winter season due to affordable space heating. Informal conversations with hotel representatives revealed that the MHPP had reduced the hotel's energy costs by half. Furthermore, other commercial entities such as general stores, tailors, welders, carpenters, and various cottage industries were also benefiting from more reliable power supply, ensuring a continuous source of income. Discounted tariffs for public buildings and a proper business model to generate and distribute revenues from the MHPP project was a key factor in the case-study's success.

These economic indicators are taken as a key measure of project success, as highlighted by one representative of the government:

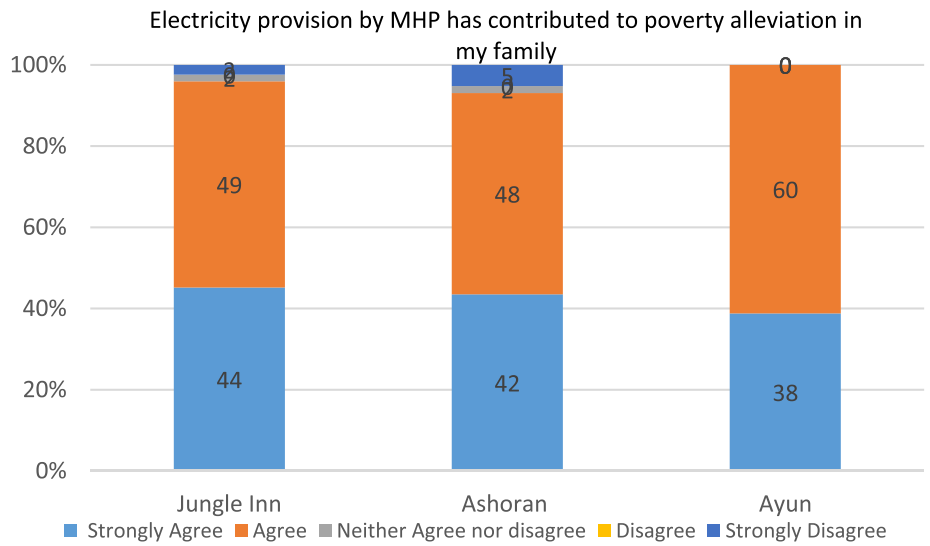

Figure 3. Survey responses to question on contribution of MHPP electricity provision on household poverty alleviation.

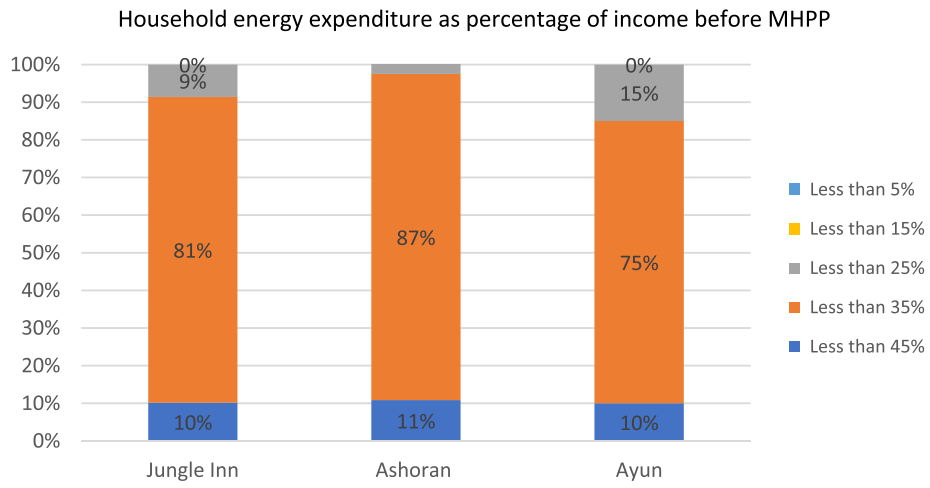

Figure 4. Percentage of household income spent on energy expenses before the MHPP.

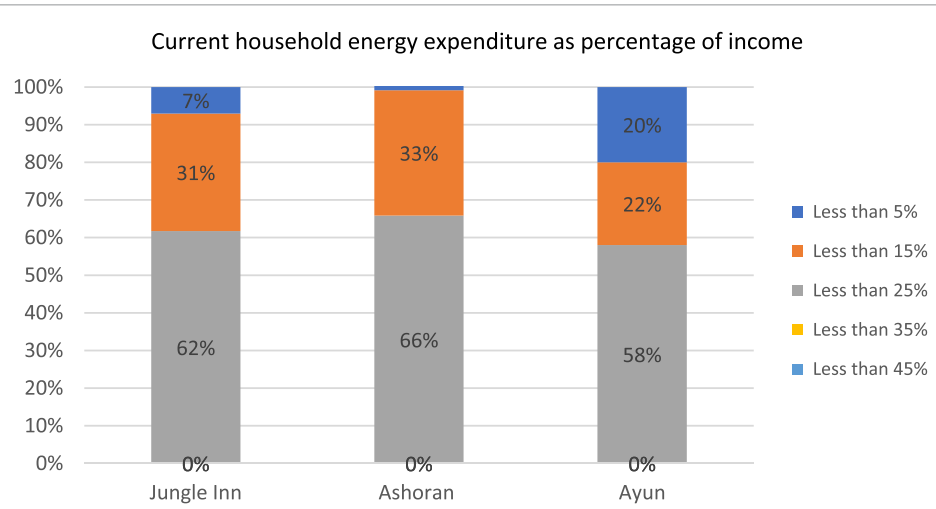

Figure 5. Percentage of household income currently spent on energy expenses.

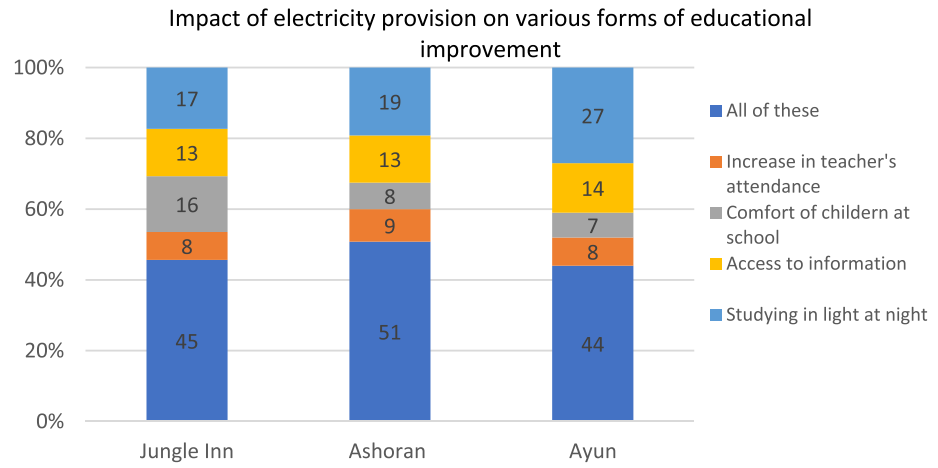

Figure 6. Impact of electricity provision on education through various means.

> "*We measure the success of projects in socio-economic impacts. We have offered electricity for the first time in remote hilly areas that have no access to national grid. Schools and hospitals have been electrified. Enrolment in schools has been increased. People now have televisions, cellular phones, washing machines and electric iron. Micro hydro projects have brought revolutionary changes in life of local communities*". (Male, major government department)

As mentioned, a key change brought about by electricity provision is seen in the operation of educational institutions and healthcare facilities that exhibit markedly improved service delivery. Electricity availability has positively impacted education and literacy rates in the case-study sites. Most respondents acknowledged their increased access to information through televisions, radios and smartphones, which have also contributed to their knowledge, awareness and education.

Overwhelmingly, the respondents perceived an observable improvement in education of the community households after provision of MHPP electricity. Survey data from the case-studies revealed unanimous agreement among respondents that MHPP-derived electricity had facilitated nighttime studying (figure 6). Other factors included a perceived increase in both student and teacher attendance. In some cases, the provision of discounted tariffs or free electricity to schools was particularly highlighted as a key factor impacting educational attainment. However, satisfaction levels varied across the sites, with slightly lower satisfaction reported in Kalam compared to Chitral. Several distributional factors contribute to this variation. For instance, the largest school in the Ashoran area primarily uses a solar system for its electricity needs. Moreover, MHPPs in Kalam were applying commercial-level tariffs to schools, which were unfavourably received by local communities. In some communities in Chitral, the pre-existing high attendance rates and educational standards have meant that the introduction of MHPP electricity did not markedly alter the status quo. Furthermore, schools in some beneficiary communities in Kalam were already equipped with alternative electricity sources prior to the MHPP installation, leading some respondents to recognise the general benefits of electrification for education but not attribute these directly to the MHPPs. This is further corroborated by the responses relating to girls' enrolment in local schools because of electrification. Whilst improvement in rates is evident across the board, these are especially apparent in Kalam, with 57% respondents strongly in agreement (figure 7).

Respondents generally noted high satisfaction with the MHPP installations (figure 8), contending that electricity access had positively affected their general work patterns, and resulted in ease of work at home. Emphasis was given to the gendered dimension of MHPP outcomes in the questionnaire survey to understand the distributional impact of improved electricity provision on women's everyday routines and practices. Energy access is seen as a critical tool for women's improvement in the region by the RSPs that have for decades given particular attention to women's socio-economic status and livelihood development (e.g. AKRSP 2020). The RSP reports and literature show that many programmes and trainings have been specifically designed for this objective, while periodic gender audits have also been undertaken to assess impact on women's socio-economic empowerment.

Findings suggest that the availability of electricity has indeed benefited women. Improved medical facilities for women have resulted in women's improved access to health care (figure 9(c)). Figure 9(a) illustrates that the majority of respondents reported being satisfied or very satisfied with the contribution of

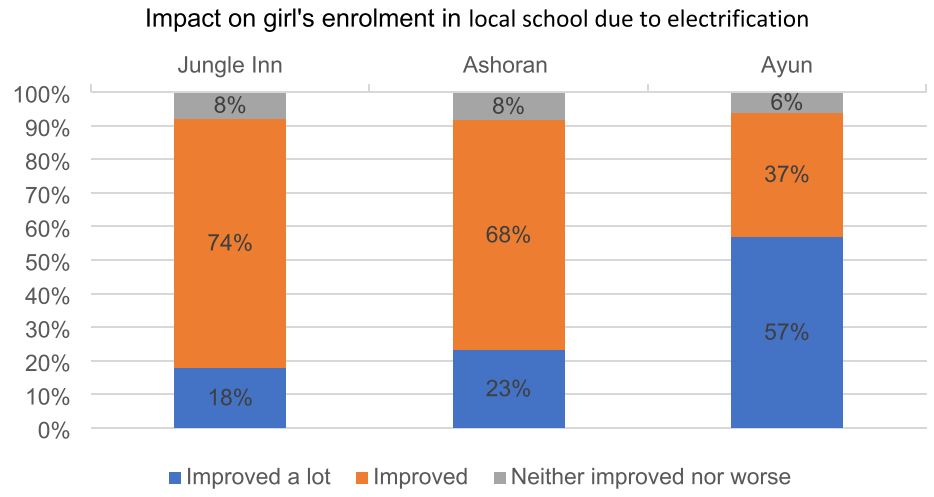

Figure 7. Impact of electrification on girl's enrolment in local schools.

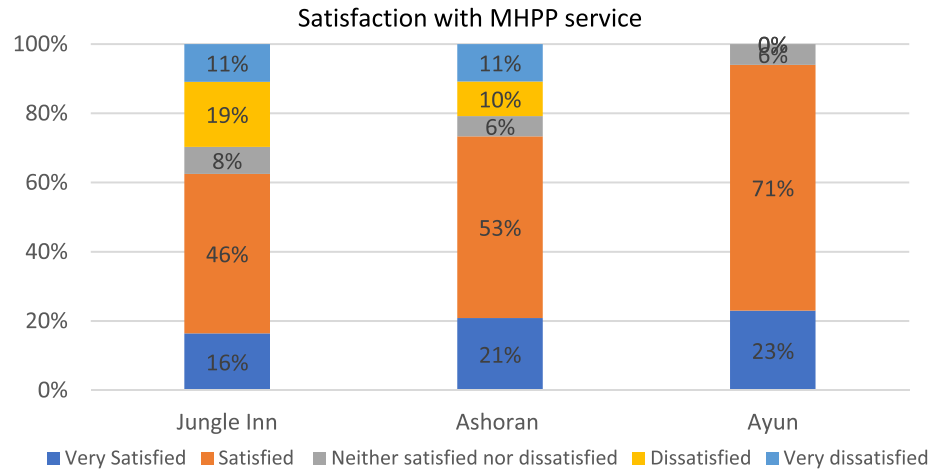

Figure 8. Survey respondents' satisfaction with MHPP service.

electrical energy to easing domestic work for women. In the Kalam case-studies, most responses indicated 'satisfied,' whereas, in the Chitral area, the majority were 'very satisfied.' This discrepancy largely stems from the differing cultural and socioeconomic contexts of the two locations. Kalam has relatively lower levels of education and development, and sees lesser women's participation in the workforce, consequently resulting in lower gender equality compared to the Chitral district. Notably, Chitral boasts some of the highest education levels for women in the province and more favourable economic conditions (Pakistan Bureau of Statistics 2021). These factors also facilitate greater access to and acquisition of labour-saving electrical appliances such as washing machines and sewing machines, further enhancing the ease of domestic work for women. Further, the data showed that two-thirds of women in Chitral had experienced improvement in their ability to take care of their children after getting access to electricity, although this perceived improvement was less pronounced in the Kalam region (figure 9(d)).

Having said this, some earlier assessments of community-driven projects show that most women's programmes had focused more on credit and less on reducing drudgery (Ahmed *et al* 2009). In the present case, we found that MHPPs have had less impact on cooking practices. Surveys indicated high levels of dissatisfaction with current cooking technologies (figure 10(a)). Responses reveal that most households continued to use inefficient cookstoves and fuelwood for cooking (figure 10(b)) and since women are traditionally responsible for most cooking practices at home, this indicates that women still face the drudgery of using inefficient technologies and risk the adverse health effects of polluting fossil fuels. However, the implementation of MHPPs has resulted in some improvements in indoor atmospheres as the need for burning biomass inside living or sleeping areas to keep warm during the winter season has decreased, as has the time required for collecting wood (figure 10(c)). Across the case-study sites,

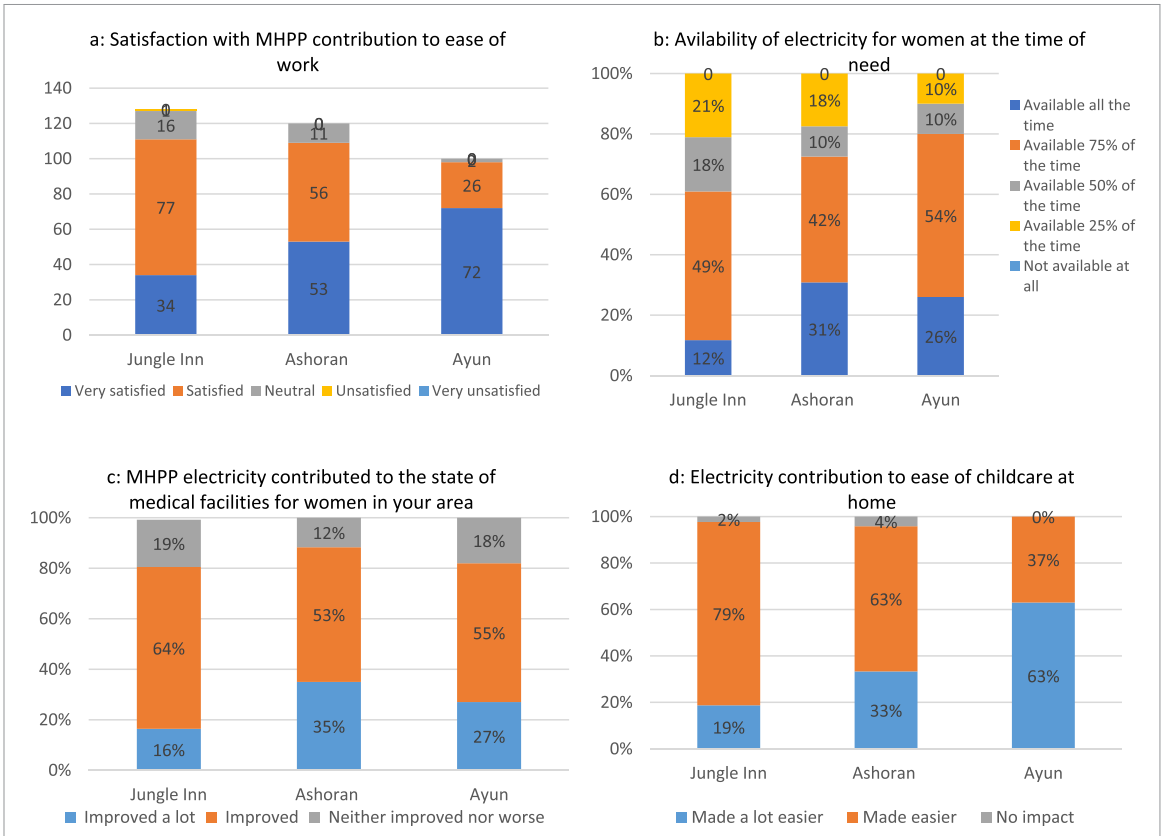

Figure 9. Perceived impact of MHPP electricity on women's (a) ease of work; (b) availability at time of need; (c) access to medical facilities; and (d) ease of childcare at home.

respondents indicated a willingness to use more electrical equipment, particularly washing machines, electric cookers and switching to electrical heating, provided that it did not cause a financial burden. This also speaks to the success of the larger mini hydro-power plants, compared to micro projects, that are able to deliver on the community's growing energy needs and vital for socio-economic empowerment, subsequently enabling their self-reliance and resilience.

Similarly, a key indicator for women's empowerment is their engagement in entrepreneurial activities as a means of income generation and hence improved socio-economic status in society. To evaluate MHPPs impact on women's enhanced entrepreneurship, respondents were asked whether women had taken up any entrepreneurial ventures which would not have been possible without the electricity provided by MHPPs. The responses for the three case studies are summarised in figure 11. Analysis shows that close to one-fourth of the respondents in the Jungle Inn and Ashoran case-studies experienced an uptake in entrepreneurial activities undertaken by women, whereas in the Ayun case-study in Chitral, the perceived uptake was higher with one-third of respondents in agreement. It is important to note that entrepreneurial activities in these communities are predominantly centred around home-based cottage industries, sewing, and hospitality services. The improvement in domestic work efficiency, facilitated by the availability of electric power, increases the amount of free time available to women, enabling more women to pursue entrepreneurial ventures, although this may also mean additional burdens and time pressures (Chant 2008, Najam-us-Saqib and Arif 2012). Having said this, our phase 1 survey across the 40 sites strongly indicated that the majority of women had, in fact, not taken on any entrepreneurial enterprises post the availability of electricity. This is similar to studies in other countries which show that whilst MHPPs impacted educational outcomes for women, positive employment-related effects were dominantly observed by men (Subedi *et al* 2023). Part of the reason may be the limited availability of non-agricultural employment opportunities (Luqman *et al* 2013) and alternative rural livelihoods (Ahmed *et al* 2009). Nevertheless, as an indicator of empowerment, these relatively low levels of women's entrepreneurship are emblematic of the wider patriarchal and gendered disparities in the region (Ummar *et al* 2008, Grünenfelder 2013, Khan 2015). This is especially concerning when considering the magnitude and length of efforts undertaken by RSPs in the last 30 years to improve women's standing and enhanced livelihoods. This is besides the fact that gendered roles and responsibilities and the division of labour, particularly within the home, seem to have remained intact, despite women's

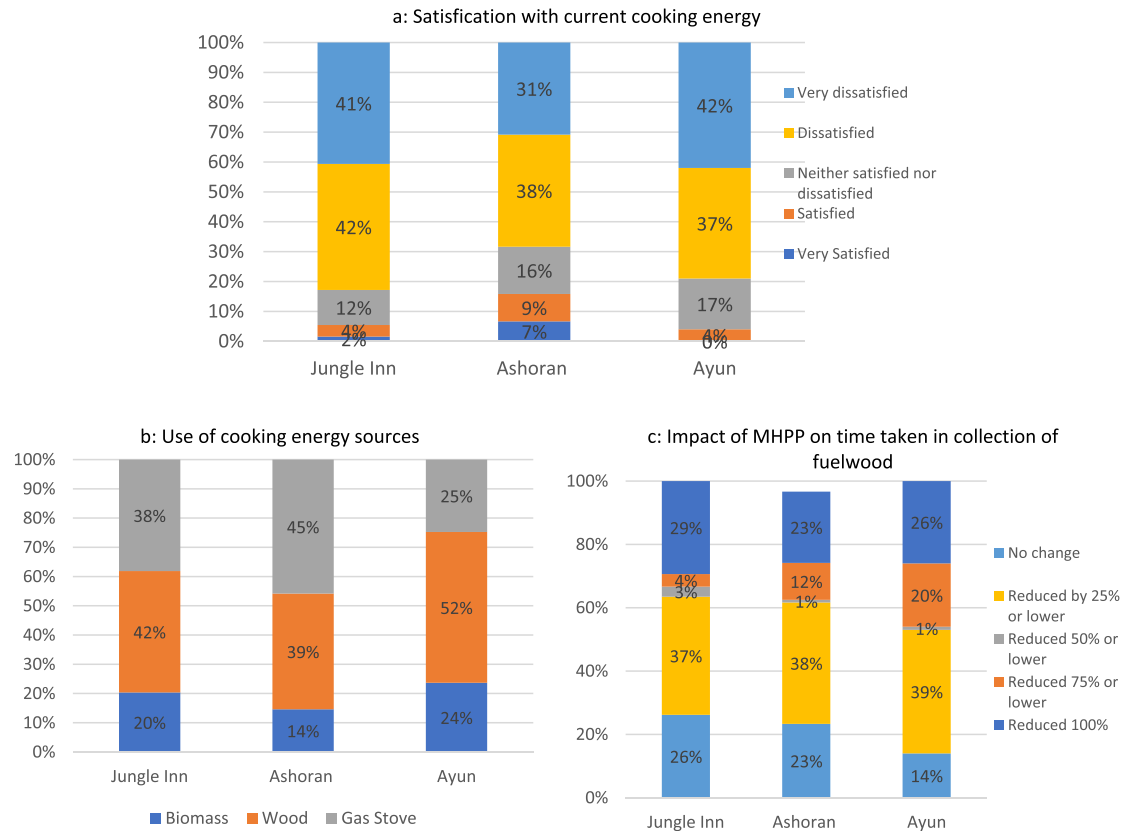

Figure 10. Respondents' satisfaction with and use of cooking energy fuels.

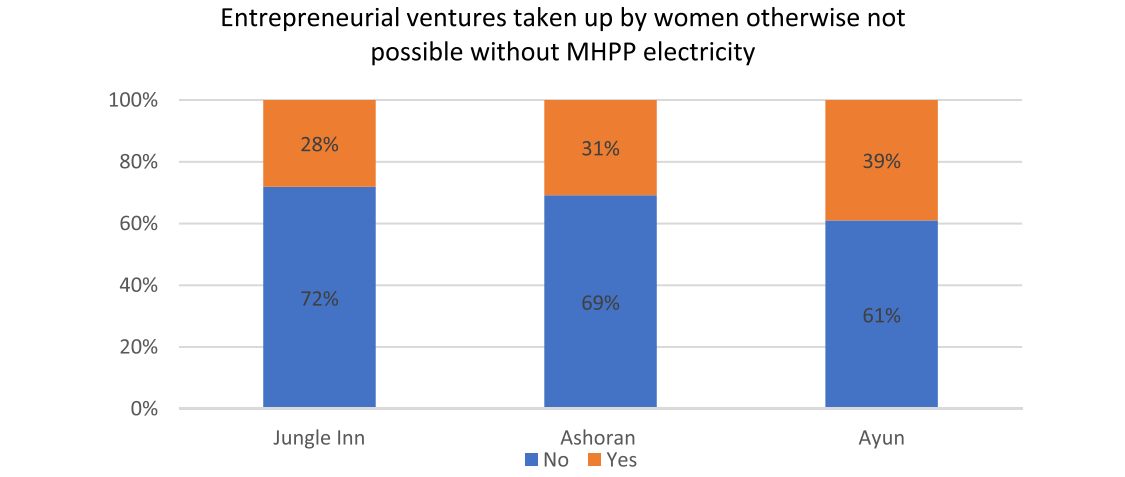

Figure 11. Entrepreneurial ventures taken up by women otherwise not possible without MHPP electricity.

increasing economic activities, which points to the continued unequal gender relations in the region (Tanwir and Safdar 2013).

4.2. Community MHPP processes: challenges of decentralised governance

As CEPs, MHPPs primarily revolve around the principles of community ownership and participatory decision-making, albeit involving a nuanced set of stakeholders, as mentioned earlier, depending on situated specificities. Wide variations existed in organisational systems and community participation within MHPPs under the RSP programmes, based on size but also other sectarian, cultural and religious factors. With regards to infrastructure projects, as previous studies (Maier 2007, Ahmed *et al* 2009) note, whilst their implementation has mostly been effective and cost efficient, there have been sustainability concerns.

Although the outputs of MHPPs in terms of service delivery are relatively easier to visualise (although causal impact may be harder to estimate), determining the success or failure of the processes involved offer a more challenging and complex picture. Several social and technical factors emerged as critical to the operation of MHPPs. Field observations suggest that where the MHPPs have become non-operational or, in some cases, are not working to full capacity, technical issues such as inadequate maintenance, lack of local technical expertise, insufficient technical training, lack of availability of spare parts and poor project design (e.g. in terms of the durability and efficiency of the turbines and generators) played a role. In a former MHPP assessment, Maier (2007) found that a key reason for the abandonment of MHPPs were environmental conditions such as sedimentation, water flow variability, and extreme weather conditions. MHPs were found to be strongly physically vulnerable to natural hazards that could easily destroy the physical infrastructure. Incidents of earthquakes, landslides and flooding have in recent decades increased in northern Pakistan, which faces extreme vulnerability to climate change (ADB 2017). In addition, increasing droughts have become a serious problem by limiting the availability of water to produce electricity. Field observations confirmed that variable and reduced water flows were critical issues affecting MHPP operation. Regrettably, many sites lacked proper record-keeping on hydrological data and water flow variations. To ensure effective project implementation and sustainability, robust data management and comprehensive environmental assessments are essential. Whilst Pakistan's Environmental Protection Act 1997 mandates Environmental Impact Assessment (EIA) for major hydropower projects, a less thorough Initial Environmental Examination (IEE) is necessary for projects with installed capacities of less than 50 MW, unless situated in an ecologically sensitive region (Butt *et al* 2024). However, although many northern areas of Pakistan fall under this category, comprehensive EIAs remain limited. Where they are undertaken, EIAs often fall short of international standards (Brown *et al* 2019) due to inadequate capacity, poor quality screening, lack of transparency, incomplete assessments and insufficient integration into project planning and decision-making (Nadeem and Hameed 2008), thus failing to account for the full environmental consequences of proposed projects. Further, effective public participation is frequently lacking in the EIA processes for MHPPs (Nadeem and Hameed 2008). This results in less community input and lower acceptance of projects, leading to implementation challenges and affecting long-term resilience.

MHPPs process efficacy can only be assessed through proper monitoring and evaluation (M&E). Although AKRSP underwent stringent M&E processes with evaluations by the World Bank's Operations Evaluation Department (OED) in 2002 and by UKDFID in 2008 (Ahmed *et al* 2009), there has been a notable absence of subsequent international assessments of RSPs. Limited international assessments in the region post-early 2000s may be linked to the political instability, increased incidents of violence and growing mistrust of NGOs in the region (Iqbal 2006, Hunzai 2013). This lack of ongoing evaluation and assessment raises significant concerns regarding the sustained impact and effectiveness of community initiatives and infrastructure projects-a concern consistently highlighted in earlier studies (e.g. World Bank 2002). Limited post-implementation assessments are also attributed to the lack of sufficient donor and aid-related funding and availability of trained personnel, especially when RSPs are overstretched (Ahmed *et al* 2009). There is a stark absence of standardised data on infrastructure status and utilisation post-project completion. During site visits, we were unable to find any evidence or documentation on the closure of the many non-operational MHPPs. This gap significantly hampers any comprehensive assessment of project failure. Although Ahmed *et al* (2009) note that the dormancy of a community organisation is not necessarily indicative of failed social mobilisation efforts, the dormancy of MHPPs, however, does suggest a potential failure to sustain decentralised infrastructure independently, leading to the redundancy of a localised community energy solution. As one interview respondent noted:

> *"In terms of sustainable operation, I would say, it's a fifty –fifty scenario. The fate of these projects depends on ability of local community to sustain quality maintenance and operations… There is a need of systematic interventions in current operational structure or enhancing community capacity".* (Male, Regional energy institute)

Although the RSPs generally have strong institutional mechanisms in place, the governance model effectively relies on sound principles of community ownership and participatory decision-making. However, notable challenges were observed in implementation, particularly regarding the clarity of roles and the equitable distribution of responsibilities. For instance, in quite a few of the 40 sites visited, appropriate steps had not been taken for the complete transfer of ownership to the local community. Surveys showed that this lack of formal agreement between the implementing and operating parties led to uncertainties around ownership, hindering effective operational management. Most respondents perceived the government as the owner of the project (figure 12), instead of the community itself, similar to findings from previous research (Elahi *et al* 2015). As literature suggests (Parish 1999, World Bank 2002, Settle 2012), the community's perceived ownership is a central objective of participatory development models and plays a significant role in

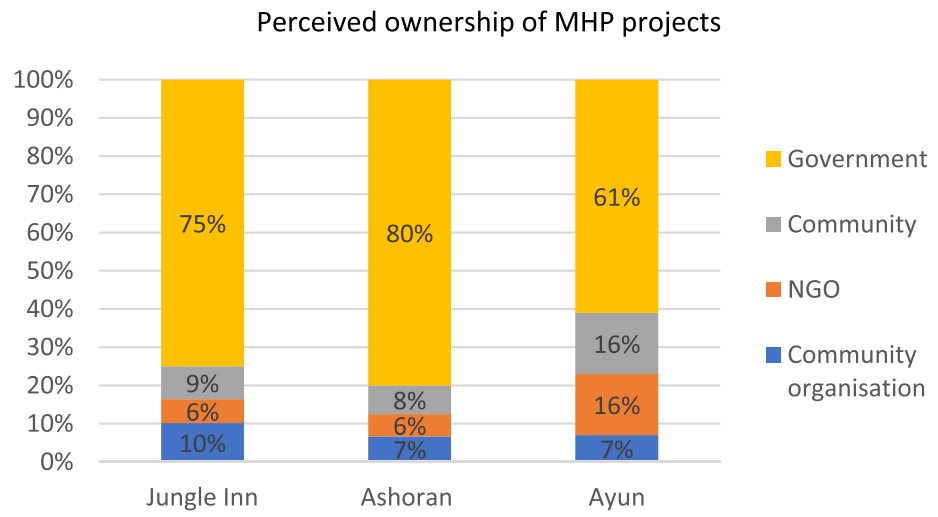

Figure 12. Survey responses on perceived ownership of MHPPs.

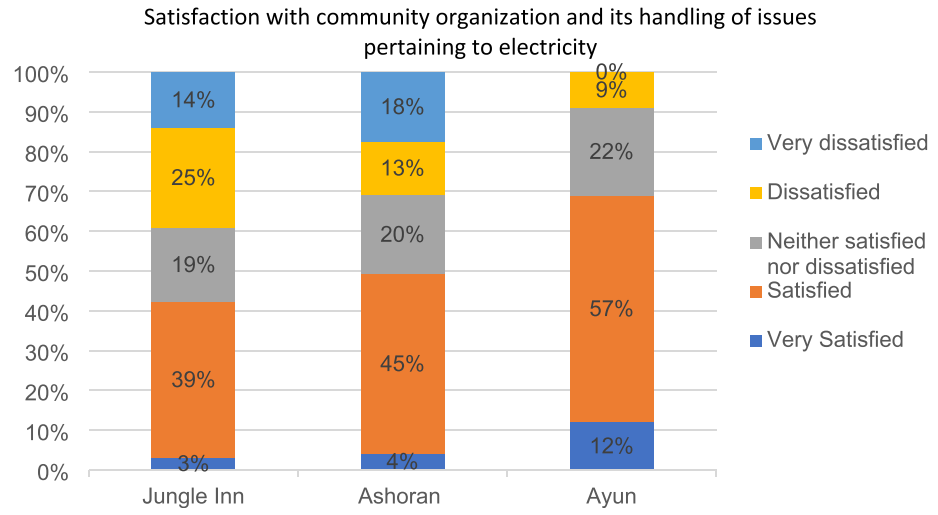

Figure 13. Respondents' satisfaction with community organisation and its handling of issues pertaining to electricity.

project success and effective long-term operation, whereas uncertainties can exacerbate conflicts and reduce community cohesion.

Field observations and informal discussions highlighted certain governance issues at the Ashoran MHPP, raising concerns among the local community. Key grievances include the perceived mismanagement of surplus funds generated from the MHPP electricity. Some community members expressed dissatisfaction over unmet promises by the government and SRSP, particularly regarding job provision for locals who contributed land or volunteered labor during the project's development and installation, indicating a mismatch between development goals and community aspirations (Parish 1999). This was further exacerbated by certain technical issues, as residents downstream reported seepage from the channel, which negatively impacted their crops and houses, resulting in economic burdens. Such issues were also reflected in community responses regarding the performance of the community organisation tasked with addressing local problems and complaints. The summarised results, as depicted in figure 13, show variations in community satisfaction across the three case studies. While the Ayun MHPP community organisation generally received positive feedback, with most respondents feeling satisfied, the levels of satisfaction were notably lower for the Jungle Inn and Ashoran MHPP.

Further, participation in CEPs is often complicated by internal community dynamics, including nepotism and power imbalances. About one-fourth of respondents indicated that the community organisation's member selection process is perceived to be tainted by nepotism (figure 14). Similar results

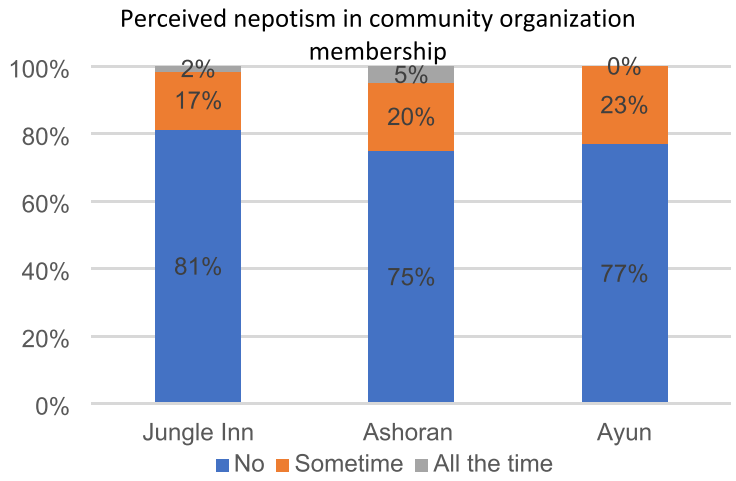

Figure 14. Respondents perceived concerns for nepotism in community organisation membership.

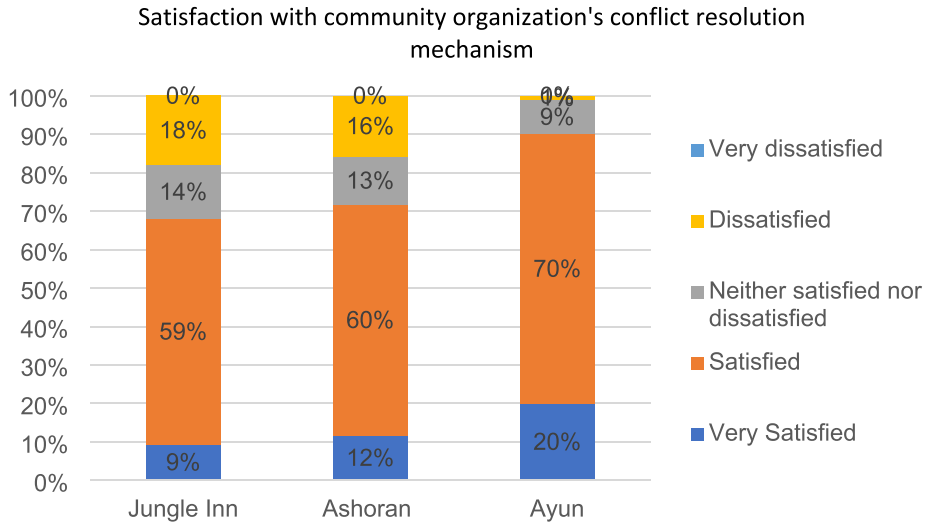

Figure 15. Respondents' satisfaction with community organisation's conflict resolution mechanism.

were also observed in Phase 1 across the 40 sites. 17% of respondents in Kalam also indicated dissatisfaction with the community organisations' conflict resolution mechanisms (figure 15).

Literature shows that participatory development models can reinforce existing power dynamics within communities (Cooke and Kothari 2001), and in the present case, community organisations lacked sufficient safeguards to prevent elite capture and ensure robust accountability (Settle 2012). Undemocratic processes can therefore lead to skewed decision-making processes where certain groups or individuals (such as wealthy men and landlords of specific ethnicities, as demonstrated by Elahi *et al* (2015)) wield disproportionate influence, leading to procedural injustices, often to the detriment of collective interests. Previous studies have also highlighted distributional injustices embedded in project processes where benefits do no reach the poorest and most vulnerable groups (Ahmed *et al* 2009, Settle 2012, Luqman *et al* 2021). This can affect overall project acceptance and sustainability, as those who feel marginalised or excluded are less likely to support the initiatives. These results are also emblematic of wider religious, political and cultural polarisation in the region that results in exclusionary tactics and can also lead to sectarian violence (Hunzai 2013, Baloch and Bugti 2018), while impacting project maintenance (Khwaja 2002). Such divisions have also penetrated the non-profit sector in Pakistan, with propaganda against NGOs being at its peak during 2006–09 (Elahi *et al* 2015). This also led to the proliferation of sectarian organisations, and growing mistrust between different rural support organisations due to their ideological divides (Iqbal 2006). Such conflicts often arise from the lack of state governance in the region that creates power vacuums resulting in sectarian contestations and struggles for politico-economic capital and control. Further, Settle (2012) notes that RSP's lack of engagement with the government and construction of parallel institutions through the VO system has

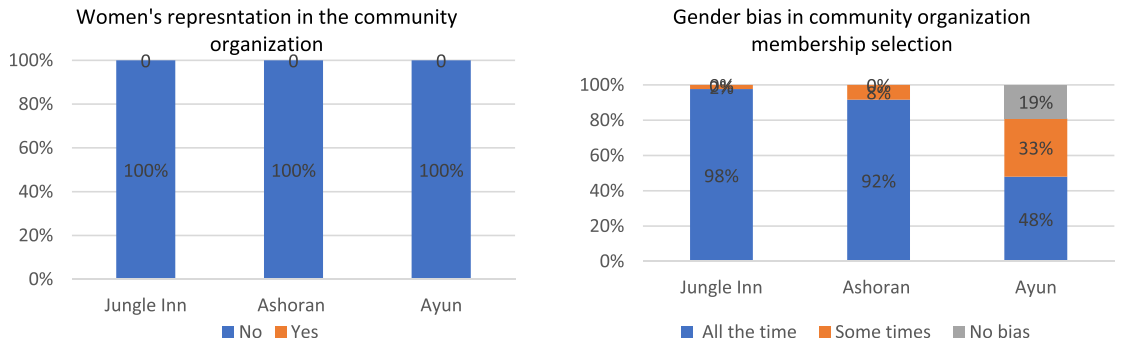

Figure 16. Respondents' perception of women's representation and gender bias in community organisation membership.

weakened the development of government capacity in the region. Moreover, despite decades of engagement, RSP's have not yet succeeded in achieving their initial goals of significant regional poverty alleviation and social mobilisation[7]. Whilst this is partly because development efforts regressed during the 2006–09 militant threats, but also the result of inadequate participatory development processes, distributional injustices in resource allocation and bureaucratic hindrances (Elahi *et al* 2015). This shortfall raises concerns about the effectiveness and resilience of community organisations, and the resulting CEPs aimed to become self-reliant entities (Ahmed *et al* 2009).

Another noticeable gap in the equitable governance of the case-study MHPPs was the complete lack of women participants in decision-making. In the three case-studies, none of the community organisations included female members (figure 16). To explore this further, respondents were asked about potential gender bias in the selection process for community organisation membership. As depicted, a significant bias was perceived, particularly in the MHPPs in Kalam, where nearly all respondents believe that gender bias consistently influences membership selection. Conversely, in the Ayun case-study, perceived bias was less pronounced. This variation can largely be attributed to the differing cultural contexts of the two regions. Kalam, culturally more conservative and predominantly Pashtun, adheres strictly to practices of female domesticity and patriarchal gendered norms (Ummar *et al* 2008, Khalid *et al* 2022). In contrast, Chitral has experienced significant social development initiatives which have focused on enhancing women's participation in the workforce and in education (AKRSP 2020). These results are evidenced even though SRSP has had a gender policy in place since 1999 and has made strident efforts to improve gender equality in its projects through gender budgeting and women-focused training programmes. However, its own evaluations have repeatedly highlighted gaps with calls for the reinforcement of gender policies and greater focus on gender empowerment (SRSP 2013). Empirical research also shows that significant gender gaps exist between policy documentation and practices on ground (Khalid *et al* 2022).

This asymmetrical distribution in the community's participative capacity inevitably diminishes its social resilience (Lorenz 2013). Cultural and religious prejudices, together with security threats hinder women's involvement in community organisations and NGO partnerships (Khalid *et al* 2022). Further, previous studies (Elahi *et al* 2015, Khalid *et al* 2022) show that whilst development efforts have increased women's decision-making power in household matters (e.g. children's education, marriages, family disputes), their triple roles (domestic, reproductive, and economic) have not been reduced, and their participation in the economic sphere has not changed gender relations or lessened their domestic burdens. Whilst CEPs have responded to women's practical needs, studies show that less attention has been given to women's aspirations and their role as potential public citizens (Ahmed *et al* 2009). This was also indicated during the interviews:

> *"True socio-economic change is not possible with gender-blind policies. As per requirement of donor as well as UN Sustainable development goals agenda, gender equality is considered an integrated part of these projects… But to be honest, when it comes to involvement of women in village communities, we failed. The current socio-cultural norms don't allow us to do so. To enhance women's participation and representation, the social mobilizers jobs were only offered to female candidates. Due to harsh climate, social constrains and hilly terrains, they refused to join".* (Male, Regional Energy Institute)

[7] The KPK province continues to fall behind Punjab and Sindh in terms of per capita income. Its Human Development Index of 0.546 is below the country's average of 0.570 in 2018–2019 (UNDP 2020).

Such instrumentalised conceptions of empowerment fail to address systemic gendered inequalities that persist within a deeply patriarchal society. Further, although the RSPs have established over hundreds of Women's Organisations (WOs), studies (Grünenfelder 2013, Khan 2015, SEBCON 2016) suggest that their efficacy in fostering independence and growth remains limited. Moreover, the conception of 'gender' in development projects in northern Pakistan is often narrowly defined, focusing primarily on improving outcomes rather than addressing broader gender interests such as distribution of productive resources, power dynamics, labour division, and entrenched gender hierarchies (Khalid *et al* 2022). Consequently, there has been little significant transformation in social and gender relations, and intersectional disparities with younger, poor, illiterate women, and those from certain ethnicities, facing constraints (Ummar *et al* 2008, Elahi *et al* 2015).

Evaluations also show that few WOs have had a productive physical infrastructure project to work on (as the major focus of RSPs for women has been on micro-credit), while community organisations that focus on infrastructure projects often exclude women, limiting their potential and overlooking their energy-related needs and decision-making (Ahmed *et al* 2009, Elahi *et al* 2015). Further, issues like increased sectarian rivalry, growing instability and religious conservatism have necessitated cautious progress in some regions (Iqbal 2006), limiting women's involvement. Despite this, there has been some success where women have led Local Support Organisations (LSOs), indicating better performance, and filling leadership gaps left by men engaged in external economic activities (Rafi Khan and Rafi Khan 2012). Significantly, gender-responsive and transformative policies and practices across all interventions are required, not just those targeted at women, with improved monitoring and evaluation of gender impacts across both MHPP outcomes and processes.

5. Concluding discussion

The sustainability and success of MHPPs in KPK depend on the socio-technical resilience of both material and governance infrastructures, and in ensuring equity and justice in both project outcomes and processes. Yet, AKSRP's 2020 progress report states that, 'despite the impressive development gains of the last three decades, the development mission in GBC [Gilgit-Baltistan and Chitral] is far from accomplished. The region is increasingly facing new challenges such as rising unemployment rates among young, inequitable access to social services and increasing social and environmental fragility' (2020, p 2). This points to the urgent need for the re-evaluation of CEPs and the need to improve participatory development models that ensure community resilience against increasing energy insecurity and climate vulnerability.

Analysis of the MHPP outcomes shows that community residents have significantly benefited from electricity provision, as MHPPs have generally succeeded in improving electricity access, resulting in boosting local economies, reducing poverty, improving healthcare and educational attainment, while also contributing to women's ease of domestic work and reduced drudgery. However, satisfaction levels varied significantly between regions, with Chitral showing more positive outcomes than Kalam, likely due to its higher levels of education and economic development, underscoring the significance of socio-economic and cultural contexts. Despite these benefits, the study also identifies critical gaps. Despite some progress, gender development remains slow and at times regressive. Women's participation in development projects is low, mainly confined to skills development, and excludes infrastructure projects. While some women have engaged in entrepreneurial activities facilitated by electricity access, the majority have not seen significant changes in employment opportunities, which remain limited, confining women to household and reproductive work. Women's involvement in decision-making and local government also remains limited, and hindered by instability, military regimes, religious extremism, and patriarchal norms. These distributional benefits between men and women, in addition to women's varying levels of satisfaction with electricity provision across the different case-studies, is emblematic of structural gender disparities that persist despite the potential of MHPPs for socio-economic empowerment.

These gender disparities significantly affect the socio-technical resilience of MHPPs in KPK by undermining equitable participation, benefit distribution, effective resource management and infrastructure adaptability- all shown to improve with women's empowerment (Leder 2016, ENERGIA 2019). Although the case-study projects have been successful so far, their long-term resilience and improved functionality hinges on meaningful engagement of women in planning and execution, as their full potential (e.g. economic viability via women's economic empowerment) remains unrealised when gender inequities persist. Gender-transformative approaches in projects have proven to enhance implementation efficiency and long-term sustainability through better and more equitable outcomes, enhanced performance and community buy-in (Rafi Khan and Rafi Khan 2012, Khalid and Foulds 2021, Skakun *et al* 2021).

Moreover, analysis shows that challenges with cooking technologies persist, as many households still rely on inefficient and fossil-fuel based cookstoves, suggesting that MHPPs' impact is constrained by enduring socio-cultural practices and infrastructural limitations. Whilst our study has tried to unpack some of the

distributional differences in communities' MHPP outcomes, more research is needed from a feminist intersectional lens (e.g. Johnson *et al* 2020, Castan Broto *et al* 2022) to unpack intrahousehold dynamics and intersectional differences based on religion, ethnicity, class, income and education for a more robust analysis of CEP resilience.

Findings suggest that although MHPP processes can vary significantly based on size, project design, cultural values and the stakeholders involved, robust community engagement and ownership is critical for their successful operation. Whilst the potential for cost-efficient and effective infrastructure through MHPPs exists, CEPs can often struggle with defining and implementing socio-technical resilience effectively. Analysis showed that MHPPs frequently fall short in robust technical design, assessment, monitoring, and evaluation, which are essential for responding to and recovering from environmental challenges (Helmrich *et al* 2021). Further, they may not fully encapsulate social resilience due to inequitable governance and 'exclusionary infrastructure' (Varley 2015) that perpetuate power imbalances, reducing social resilience and increasing long-term infrastructural vulnerability (Graham and Marvin 2001, Lorenz 2013). Additionally, the democratic nature of these projects can be compromised by the co-option and coercion by local power elites, leading to injustices in the distribution of benefits and neglect of community-specific needs and aspirations. More democratic and equitable participatory models are critical for sustainable infrastructure development.

To mitigate these risks, strengthening local institutions and enhancing their administrative and managerial capacities are crucial steps toward ensuring the success and sustainability of CEPs. Adaptive management practices are essential to respond to the dynamic environmental, technical, and social changes. This also requires flexibility in project design to tackle unforeseen challenges such as water flow variability, technical malfunctions, and imminent climate change impacts. Focusing solely on technical resilience does not guarantee infrastructure success, especially in contexts that require adaptation to political uncertainties Continued political unrest and insecurity, if unaddressed, will persistently hinder development efforts in KPK. KPK's marginal role in Pakistan's federal structure also contributes to its limited development capacity, and despite governance reforms, the region remains heavily reliant on foreign aid for development. However, the limitations of donor-led projects, as highlighted by Settle (2012), can restrict community-specific interventions and impose dependency due to their rigid objectives and temporary funding cycles. Therefore, building local capacities, diversifying funding and developing alternative governance frameworks is critical for infrastructure resilience.

To enhance accountability and transparency in development work, there is a need for more rigorous evaluations and assessments. These should measure both the short-term outputs and long-term impacts of projects, providing clear, actionable feedback to all stakeholders. In this regard, several governance models may be employed. For micro-projects requiring frequent maintenance, a feasible option is to lease these out to a local partner, who would share costs and benefits with the government. Alternatively, adopting a social enterprise model or establishing public-private partnerships that are both community-driven and supported by the government could offer more sustainable solutions. In the social enterprise model, the existing RSPs or NGOs can be responsible for operation and maintenance, whereas community organisations can ensure community engagement, determine tariffs and oversee conflict resolution. The local government can be responsible for overall supervision. Profits from the project can be equitably re-invested into socio-economic development initiatives for the community in an inclusive manner, giving due consideration to poor residents, women and vulnerable households. These models can promote local ownership and investment, enhancing community self-reliance and resilience. Moreover, government backing, through strengthened institutions and management, can ensure these models align with broader development policies and deliver equitable benefits (Ahmed *et al* 2009). Additionally, ensuring the appropriate scale for projects like MHPPs is vital (Yadoo and Cruickshank 2010), alongside integration with other renewable energy strategies, for example for cooking (Batchelor *et al* 2022), not only for their technical resilience but also for developing socio-economic resilience by adequately meeting the community's energy needs.

As climate change intensifies and natural disasters become more frequent in northern Pakistan, the need for infrastructure resilience in CEPs becomes increasingly critical. Future research should focus on enhancing MHPPs' adaptability to climate stresses and their contribution to local and regional resilience through a socio-technical lens, ensuring continued vital energy support to communities.

Data availability statement

The data cannot be made publicly available upon publication because they contain sensitive personal information. The data that support the findings of this study are available upon reasonable request from the authors.

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