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From Energy Poverty to Off-Grid Smart Energy: Measured Household Air Quality and Willingness to Pay in Skardu, Gilgit-Baltistan

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Abstract

Gilgit-Baltistan lies at the periphery of Pakistan's electricity network, and in Skardu the consequences are acute. The town sits at 2,228 m, receives no piped natural gas, and endures a heating season of four to five months in which night temperatures fall between −10 and −20 °C. More than 80% of households therefore burn wood, dung cakes, crop residue, kerosene, coal, or plastic waste for warmth and cooking. This paper asks two questions: what the present fuel regime costs the people who live with it, and whether those people would pay for an alternative. We deployed low-cost optical particulate sensors indoors and outdoors through the 2023 heating season, applied a radiative forcing model of black carbon deposition to nearby glaciers, recorded household fuel expenditure, and sized an off-grid photovoltaic and storage system for the site. Measured indoor PM2.5 varied sharply by configuration: 359 to 463 µg/m3 with a wood Angeeti stove, 306 to 382 with cow dung, 261 to 375 with a kerosene heater, and 48 to 149 with a liquefied petroleum gas appliance by day, rising to 399 to 409 in that same room during the evening pollution peak. Indoor carbon dioxide reached 4,711 ppm, confirming that rooms are sealed against the cold to the point of eliminating ventilation. Outdoor daily air quality index values at the main bazaar peaked at 467. Modelled black carbon deposition adds an estimated 1 to 3 mm of water-equivalent melt per day on nearby ice. Sized on January irradiance, a 1.5 kWp array with 4 kWh of storage delivers electricity at about PKR 55 per kWh for a capital outlay near two winters of the fuel spend the highest-spending surveyed household already reports.

Keywords: Black carbon, distributed generation, energy access, high-altitude communities, willingness to pay.

1. Introduction

Electricity reaches most of Pakistan, but the national average conceals the places it does not reach. Remote mountain districts sit at the far end of long transmission lines or beyond them altogether, and extending a central grid into that terrain is slow and expensive work that rarely repays its cost. The national picture is well documented: dependence on imported fuel, costly generation, and control equipment older than the assets it monitors [1]. Transmission and distribution losses rather than any shortage of installed capacity account for much of the shortfall, and a succession of smart grid programmes has delivered less than intended [2]. For a valley town in the Karakoram, waiting for that grid to arrive is not a strategy.

Skardu makes the abstraction concrete. The town sits at about 2,228 m in Gilgit-Baltistan, loses mains supply for as much as nine hours a day, and endures a heating season of four to five months in which night temperatures drop between −10 and −20 °C. No natural gas is piped in. What fills the gap is combustion: wood, dung cakes, crop residue, kerosene, coal, and, in the poorest homes, plastic waste. Roughly four in five households heat and cook this way.

Designing an alternative for such a place requires more than a solar resource map. Two questions come first. What does the current fuel regime already cost the people who live there, and would those people actually pay for a replacement? We answer both with field data collected in Skardu during 2023.

This paper makes three contributions. First, we report device-resolved indoor particulate and carbon dioxide measurements for the four heating and cooking configurations in common local use, which to our knowledge is the first such dataset published for Skardu. Second, we pair those measurements with outdoor monitoring and a first-order black carbon melt model to trace a single emission source through health, valley air quality, and cryospheric effects. Third, we set that quantified burden alongside demand-side evidence from a household and small-business survey, so that the cost of the status quo and the willingness to leave it are measured in the same community and the same season.

The remainder of the paper is organised as follows. Section 2 reviews the literature this work sits within. Section 3 describes the valley and its energy context. Section 4 sets out the monitoring, survey, and modelling methods. Section 5 reports the measured cost of the present fuel regime and the survey findings. Section 6 develops an off-grid architecture and a phased financing roadmap. Section 7 considers implications and limitations, and Section 8 concludes.

2. Related Work

Four bodies of literature bear on this study, and each leaves something unfinished.

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The first concerns the readiness of Pakistan's network for modernisation. Raza *et al.* [1] catalogue its weaknesses bluntly: mismanagement, dependence on imported fuel, expensive generation, and obsolete monitoring and control equipment. They propose a standards-based model and evaluate it through SWOT and STEEPLE analysis. The value of their work here is diagnostic. If the central network struggles this much, peripheral valleys will not be reached by incremental extension in any relevant timeframe. Nazir and Sharifi [2] reach a compatible conclusion from another direction. Using Delphi consultation with sector experts and interpretive structural modelling, they rank nine interlinked barriers to smart grid deployment. State monopoly and low public awareness sit at the base of their hierarchy, with financial constraints, weak regulation, and unmodernised infrastructure above. Two of those barriers, cost and awareness, reappear directly in our results and shape the financing model we propose.

The second concerns air quality in northern Pakistan, where the evidence base is thin. Hussain *et al.* [3] provide the first seasonal characterisation of urban air quality in the region, reporting a filter-based winter mean $PM_{2.5}$ of 51.8 $\mu g/m^3$ in Gilgit City against a summer mean of 12.5 $\mu g/m^3$, and attributing the winter burden to biomass burning. Ahmad *et al.* [4] measured five sites along the China-Pakistan Economic Corridor, finding winter $PM_{2.5}$ between 25.4 and 60.1 $\mu g/m^3$ and black carbon peaking at 16.21 $\mu g/m^3$ in Gilgit. Nasir *et al.* [5] report the only published ground measurement we could locate for Skardu itself, a mean black carbon concentration of 3.0 ± 1.0 $\mu g/m^3$. Liaqat *et al.* [6] surveyed indoor air quality in 20 high-altitude households in Gilgit-Baltistan and found $PM_{2.5}$ five times above the Pakistani ambient standard, with 65% of homes failing ventilation criteria. None of these studies reports device-resolved indoor concentrations, and none covers Skardu.

The third concerns exposure from solid fuel use more generally. Siddiqui *et al.* [7] measured 2.74 mg/m^3 of $PM_{2.5}$ in wood-using Pakistani kitchens against 0.38 mg/m^3 in gas-using kitchens, establishing the scale of the fuel gradient nationally. Fatmi *et al.* [8] review the associated health burden. The World Health Organization attributes 2.9 million premature deaths a year to household air pollution [9], and its guidelines on household fuel combustion recommend against unprocessed coal and kerosene as household fuels [10].

The fourth concerns demand. The closest analogue to Skardu is not in Pakistan. Sadik-Zada *et al.* [11] surveyed an electrified and a nonelectrified village in the Eastern Pamirs of Tajikistan and measured what changed. Household income rose by 34 to 48%, and school-age children gained between 71 and 95 minutes of study time a day. Cooking shifted away from firewood, coal, and manure, though not completely, because some households retained traditional fuels out of taste and habit. Both halves of that result matter here: the gains from electrification in high mountain communities are large, and fuel switching is a behavioural process rather than an automatic one. Bashir *et al.* [12] surveyed 400 residents of an emerging economy and modelled willingness to invest in renewables within the unified theory of acceptance and use of technology. Resource availability, knowledge, and experience of outages all predicted investment intent, with education amplifying the effect.

What none of these studies offers is a single, field-grounded account of one high-altitude off-grid community that measures the cost of the status quo and the willingness to leave it in the same place and the same season. That is the gap this paper addresses.

3. Study Area and Energy Context

Skardu Valley lies at roughly 2,228 m, enclosed by rock walls rising to between 4,000 and 6,000 m. The geometry matters more than the altitude. A basin this narrow ventilates poorly, and in winter it holds cold air near the floor beneath warmer air above, a configuration that can persist for days. Night temperatures fall between −10 and −20 °C. The heating season runs four to five months and peaks from December through February.

The local energy situation is defined by what is absent. There is no piped natural gas, no dependable winter electricity at a price households can meet, and almost no building insulation. Load shedding of up to nine hours a day is routine, and Skardu is not substantially connected to the national grid, so local supply depends on isolated hydropower plants. More than 80% of homes therefore burn biomass, dung cakes, plastic, coal, or kerosene for warmth and cooking alike; the 2016 to 2017 Multiple Indicator Cluster Survey for Gilgit-Baltistan records 84.8% of households using solid fuels as their primary cooking fuel [13].

The building stock compounds the problem. Walls are stone and mud, roofs cement or mud, rooms small and frequently single. Chimneys are absent or poorly designed. Airflow is deliberately minimised, since every draught represents heat lost. Smoke accumulates indoors and then leaks outward through gaps, windows, and doorways into the valley air. The result is a place where household energy poverty, valley-scale pollution, and black carbon deposition on nearby ice can be observed together. No government air quality station operates here.

4. Methods

4.1. Air Quality Monitoring

We measured particulates with low-cost optical sensors: IQAir AirVisual Pro units indoors and an AirVisual Outdoor unit outside. Both operate by laser light scattering and report PM_1, $PM_{2.5}$, and PM_{10} alongside temperature, relative humidity, carbon dioxide, and the United States Environmental Protection Agency air quality index (AQI). Logging ran at five-minute intervals, with data transmitted over a cellular link.

Placement followed exposure rather than convenience. Indoor units were installed in occupied living rooms and kitchens at 1.5 m above the floor, set back from direct stove airflow so that readings reflected breathing-zone conditions rather than plume centres. The outdoor unit was mounted about 3 m above ground at the Main Bazaar in Skardu, the busiest pedestrian area in the town, sheltered from precipitation and clear of walls and vehicles.

Sensor data from a subzero winter require verification, so we ran four checks. Indoor and outdoor units were co-located for 24 hours to establish agreement. A controlled incense burn confirmed that units responded consistently through both the rise and the decay of a particulate event. Readings taken at high relative humidity were flagged and inspected, since laser scattering degrades through hygroscopic growth above roughly 70 to 78% relative humidity [14]. Winter conditions in Skardu remained predominantly below that threshold. Finally, we compared our record against a national low-cost $PM_{2.5}$ network spanning six climatic zones of Pakistan, which allowed us to separate local events from regional ones.

Three limitations of the instrument and the record deserve statement in advance. First, independent evaluations of the AirVisual Pro report correlation coefficients against reference instruments of 0.85 to 0.93 but absolute errors that grow with relative humidity and vary in sign between studies [15, 16]. We therefore treat the measured concentrations as robust indicators of magnitude and of relative differences between configurations, and not as reference-grade absolute values. Second, the archived record available for analysis comprises timestamped captures of the instrument display taken during monitoring sessions rather than the complete logged series, which was not retained. We therefore state the number of distinct samples behind every configuration in Table 1, and the statistics we report summarise those samples rather than a continuous distribution. Third, the AQI is defined by the Environmental Protection Agency on a 24-hour average concentration, and all index values above 300 fall in a single Hazardous category. We report the index because it is what the instrument displays and what the community reads, but we anchor the analysis to the underlying mass concentrations wherever possible.

4.2. Exposure Estimation

Inhaled dose follows the standard relationship

$$D = C \cdot IR \cdot t \tag{1}$$

in which C is the measured $PM_{2.5}$ concentration ($\mu g/m^3$), IR is the inhalation rate (m^3/h), and t is the duration of exposure (h). We adopt an activity-weighted indoor inhalation rate of 0.6 m^3/h for an adult and 0.4 m^3/h for a child, values that sit between the sedentary and light-activity rates tabulated by the United States Environmental Protection Agency for indoor occupancy [17].

4.3. Household Energy and Willingness-to-Pay Survey

Eight units were surveyed face to face across Skardu and the nearby settlements of Kachura and Shigar: six households and two hotels. The questionnaire covered whether energy needs were being met, which fuels and appliances were in use, what electricity and fuel cost each month, what difficulties respondents faced, and whether they would adopt and pay for a renewable or hybrid system. Informed consent was obtained before each interview.

Eight is a small number and we treat it as such. These responses are indicative field evidence about expenditure and preference in this valley. They are not a representative sample of Gilgit-Baltistan, and we draw no population-level inference from them.

4.4. Black Carbon Melt Modelling

Black carbon leaving a Skardu chimney can settle on ice a few kilometres away, and once there it darkens the surface. We estimated the consequence using a three-step radiative forcing model of the kind applied elsewhere in data-sparse mountain regions.

The first step estimates the reduction in broadband snow albedo caused by deposited black carbon. Field and satellite studies across comparable High Mountain Asia settings report local reductions $\Delta\alpha$ of 0.03 to 0.04 in areas receiving sustained household or transport emissions [18]. The second step converts that albedo change into additional absorbed shortwave radiation at the surface,

$$\Delta F = \Delta\alpha \cdot S \tag{2}$$

where S is the incident shortwave irradiance. Taking S between 150 and 300 W/m^2 as a daily mean for winter and spring at these altitudes gives ΔF between 4.5 and 12 W/m^2. The third step converts the extra energy into melt through

$$M = \Delta F \cdot \Delta t / (\rho_w L_f) \tag{3}$$

in which ρ_w is the density of water (1,000 kg/m^3) and L_f is the latent heat of fusion of ice (3.34×10^5 J/kg). Over a 24-hour period this yields between 1.2 and 3.1 mm of additional water-equivalent melt per day.

We did not sample snow. Emission factors, albedo values, incoming radiation, and the black carbon fraction of $PM_{2.5}$ all derive from published literature, which makes these first-order estimates that establish magnitude and direction. They are not a mass-balance closure and should not be read as one.

4.5. Participatory Community Engagement

The monitoring sat inside a three-day participatory workshop run with the University of Baltistan, Skardu, and structured around an experiential cycle of understanding, observation, and action. Participants included young people, women, elders, and teachers.

They were introduced to the chain linking household fuel to indoor pollution, valley inversion, and glacier melt, then trained to operate the sensors and to log fuel type, heating schedule, ventilation state, and pollution spikes themselves. This produced context that no instrument could supply: why particular homes spiked when they did, which habits drove overnight smouldering, and who in a household actually absorbs the exposure. Women and elders, who spend the longest hours indoors, absorb most of it.

5. Results

5.1. Indoor Particulate Concentrations by Device

Indoor conditions during the heating season were hazardous in every home monitored with a solid or liquid fuel, and the concentrations separated cleanly by device. Table 1 reports the observed range across logged readings for each configuration, and Fig. 1 plots those ranges at their midpoints.

The wood-burning Angeeti produced the highest sustained loads, with $PM_{2.5}$ between 359 and 463 µg/m^3 across six distinct samples and PM_{10} between 449 and 575 µg/m^3. Cow dung followed, at 306 to 382 µg/m^3. The kerosene Fujika heater recorded 261 to 375 µg/m^3, across five samples, with sharp transients at ignition and refuelling. The room heated by a liquefied petroleum gas (LPG) appliance behaved in two distinct regimes. Through the day it was by far the cleanest space monitored, at 48 to 149 µg/m3 across ten samples. During the evening pollution peak, between 19:20 and 19:21, the same room reached 399 to 409 µg/m3 across five samples, a level indistinguishable from the wood-heated room.

The World Health Organization 24-hour guideline for $PM_{2.5}$ is 15 µg/m^3 [19]. The wood-heated room exceeded it by a factor of 24 to 31, the dung-heated room by 20 to 25, and the kerosene-heated room by 17 to 25, hour after hour, across a heating season of four to five months. The LPG-heated room exceeded it by a factor of 3 to 10 during the day and by 27 during the evening peak.

The daytime gradient between fuels is the practically useful finding. At comparable times of day, the LPG-heated room carried roughly a quarter of the particulate loading of the wood-heated room. That gap is what a clean heating intervention can capture, and it is larger than any plausible gain from ventilation advice alone. The evening convergence is equally instructive and is taken up in Section 5.2.

Applying (1) to a typical evening in a wood-heated room, four hours at the measured midpoint of 411 µg/m^3, gives an inhaled dose of approximately 990 µg of $PM_{2.5}$ for an adult and 660 µg for a child. The same calculation for the LPG room gives 205 and 137 µg respectively. The people accumulating the higher figure are mostly women, elders, and children.

Table 1. Measured indoor air quality by heating and cooking device, Skardu 2023.

Monitored configuration	n	$PM_{2.5}$ range (µg/m^3)	Mean (SD)	Median	CO_2 range (ppm)
Angeeti wood stove	6	359 to 463	409 (46)	407	1,184 to 1,836
Cow dung stove	2	306 to 382	not computed	not computed	not logged
Fujika kerosene heater	5	261 to 375	326 (55)	357	589 to 4,463
Gas cylinder room, daytime	10	48 to 149	110 (29)	109	1,578 to 4,711
Gas cylinder room, evening	5	399 to 409	405 (4)	405	1,498 to 1,691
WHO 24-hour guideline		15			

5.2. Carbon Dioxide as a Ventilation Indicator

Carbon dioxide was logged alongside particulates, and it answers a question the particulate record cannot. High $PM_{2.5}$ indicates a dirty fuel. High carbon dioxide indicates that the room is not exchanging air with the outside.

Concentrations reached 1,836 ppm in the wood-heated room, 4,463 ppm in the kerosene-heated room, and 4,711 ppm in the room heated by an LPG appliance. Values above roughly 1,000 ppm are conventionally taken to indicate inadequate ventilation in an occupied space, and every configuration exceeded that threshold for sustained periods.

The LPG room is the instructive case, and the two regimes in Table 1 explain each other. Through the day it produced the lowest particulate concentrations of any space monitored and the highest carbon dioxide, because an unvented gas appliance consumes oxygen and emits combustion products directly into a sealed room. During the evening peak the relationship inverted: carbon dioxide fell to between 1,498 and 1,691 ppm, whereas PM2.5 rose to about 405 µg/m3. Lower carbon dioxide indicates more air exchange with the outside, and at 19:20 the outside air was itself heavily loaded, as Section 5.3 shows. The particulate burden in that room at that hour is therefore better explained by infiltration of valley air than by the appliance. Two conclusions follow. Fuel switching alone does not resolve the indoor environment, because a household that moves from wood to gas without addressing ventilation trades a particulate hazard for an asphyxiation and nitrogen dioxide hazard. And clean indoor air cannot be secured house by house as long as the valley itself is polluted, because the ventilation that removes combustion products also admits whatever is outside.

This finding also explains why ventilation advice fails on its own. Opening a window cuts both the particulate peak and the carbon dioxide immediately, and it costs the household its heat just as fast. Residents choose between breathing and staying warm, and in a Skardu January warmth wins. The engineering answer is to separate the two, which is what a sealed clean-heat system with controlled ventilation does.

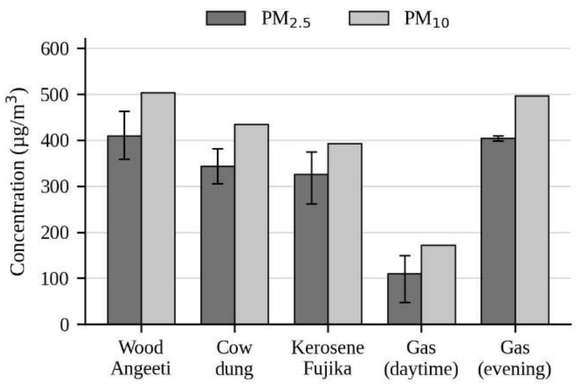

Fig. 1. Measured indoor particulate concentrations by heating device

5.3. Outdoor Air Quality and the Valley Bowl Effect

Skardu has no industry, negligible traffic, and no significant mechanical dust sources. Between 29 November and 27 December 2023, the outdoor unit at the Main Bazaar nonetheless recorded daily AQI values that remained above 190 throughout the record, exceeded 300 on most days, and reached a maximum of 467. Under the index breakpoints in force at the time of measurement, an AQI of 467 corresponds to a 24-hour $PM_{2.5}$ concentration of approximately 450 µg/m^3, or 30 times the World Health Organization guideline.

Sustained values of this magnitude across a month rule out a one-off event. This is basin-wide stagnation lasting through the heating season. The diurnal pattern identifies the source without ambiguity: concentrations climb from about 06:00 to 09:00 as stoves are lit after cold nights, fall back, then climb again through a longer evening peak between roughly 17:00 and 22:00. Those are heating hours, and they match the household heating schedules logged during the workshop.

The mechanism is the valley behaving as a bowl. Radiative cooling after sunset drains cold air to the valley floor, where it pools beneath a warmer inversion layer that acts as a lid. Wind speeds under that lid are very low. Smoke from several hundred households mixes through the lowest tens to hundreds of metres and remains there until the inversion breaks.

The instructive comparison is not with other rural areas. These concentrations are of the same order as severe urban smog episodes, and they substantially exceed the winter means reported for Gilgit City [3] and for the five China-Pakistan Economic Corridor sites measured by Ahmad *et al.* [4]. A town of this size, with no factories at all, generates air of the same order as an industrial metropolis simply by heating itself.

5.4. Fuel Toxicity and Emission Factors

Table 2 ranks the fuels in local use by health risk, where 1 is most harmful, and lists their principal emissions. Table 3 gives indicative emission factors together with the hourly emission rates these imply at representative burn rates of 1.5 kg/h for solid fuels, 1.0 kg/h for plastic, and 0.136 kg/h for a wick kerosene stove.

The biomass and coal emission factors in Table 3 derive from published compilations of domestic combustion measurements [20, [21], with South Asian cookstove field measurements as a cross-check [22]. Two entries warrant comment. The kerosene factor applies to a wick stove and should not be transferred to a wick lamp, for which measured $PM_{2.5}$ emission factors are nearly three orders of magnitude higher and consist almost entirely of black carbon [23]. All entries carry substantial uncertainty, since reported factors for a given fuel vary by a factor of two or more with stove type and combustion mode.

Plastic waste occupies the highest risk rank, and the emission factor literature supports that placement. Field measurement of sorted plastic waste burning gives a $PM_{2.5}$ emission factor of 84 ± 13 g/kg [24], roughly seven times the factor for wood in a stove, with a literature range of approximately 8 to 152 g/kg across polymer types and combustion modes [25, 26]. Combustion of mixed plastic additionally releases dioxins, furans, and heavy metals, which have no analogue in biomass smoke. We note this value explicitly because earlier compilations for this valley assigned plastic a nominal emission factor an order of magnitude below wood, which placed it inconsistently with its own toxicity ranking.

Table 2. Fuels used in Skardu households, principal pollutants, and health risk ranking

Fuel type	Main pollutants released	Toxicity rank
Plastic waste	$PM_{2.5}$, PM_{10}, CO, dioxins, VOCs, furans, heavy metals	1
Cow dung	$PM_{2.5}$, PM_{10}, CO, VOCs, methane, ammonia	2
Crop residue	$PM_{2.5}$, PM_{10}, CO, NO_2, VOCs	3
Wood	$PM_{2.5}$, PM_{10}, CO, VOCs, formaldehyde	4
Charcoal	CO (very high), $PM_{2.5}$, VOCs	5
Coal	$PM_{2.5}$, SO_2, NO_2, CO, VOCs, mercury	6
Kerosene	$PM_{2.5}$, CO, NO_2, black carbon	7
LPG	Trace PM, low CO, NO_2 if poorly burned	8 (least)

Table 3. Indicative $PM_{2.5}$ and CO emission factors with implied hourly emissions

Fuel	$PM_{2.5}$ EF (g/kg)	$PM_{2.5}$ (g/h)	CO EF (g/kg)	CO (g/h)
Plastic (mixed waste)	84	84.0	not established	not established
Wood (stove)	12.3	18.5	127	190.5
Dung cakes	9.1	13.7	113	169.5
Coal (bituminous)	8.5	12.8	150	225.0
Crop residues	7.9	11.9	124	186.0
Charcoal	0.5	0.8	170	255.0
Kerosene (wick stove)	0.07	0.01	29	3.9

5.5. Black Carbon deposition and glacier melt

Skardu sits close to major glacier systems, which gives its black carbon somewhere consequential to land. Applying (2) and (3) across the observed albedo reduction of 0.03 to 0.04 yields between 1.2 and 3.1 mm of additional water-equivalent melt per day in affected zones. This figure is derived entirely from literature-based radiative forcing parameters rather than from snow sampling at the site, consistent with the assumptions set out in Section 4.4 and the limitations in Section 7, and it should be read as a first-order estimate of magnitude and direction. Set against typical seasonal ablation rates for glaciers in the Indus and Karakoram catchments, it corresponds to an acceleration of roughly 5 to 10%. These are upper-bound figures for the populated valley margins where deposition is heaviest, and they are consistent in magnitude with the 4.6 to 6.3% snowmelt enhancement measured for anthropogenic black carbon on Central Asian glaciers [18]. Airborne black carbon has already been measured in Skardu at 3.0 ± 1.0 µg/m3 [5], and deposition on Karakoram and Himalayan ice has been documented at 17.66 µg/m3 in glacier ice [27].

What makes this more than a local curiosity is the loop it closes. Energy poverty drives polluting combustion. Combustion fills the valley and deposits carbon on ice. The ice melts faster and less predictably, destabilising the water supply on which agriculture and hydropower depend. Reduced economic resilience then makes cleaner fuel even less affordable than before, and the cycle repeats with the next winter.

5.6. Economic Burden of Household Fuel Use

The financial burden is heavy and falls hardest on those least able to carry it. Table 4 reports the surveyed responses, with all monetary values in Pakistani rupees. One large household burning its own wood reported spending PKR 150,000 across a single winter. The two hotels each consumed around 60 kg of LPG a month at roughly PKR 16,000. Electricity bills, by contrast, were small, typically PKR 500 to 3,000 a month, which reflects how few appliances run and how little power arrives rather than any abundance.

That contrast is the most useful finding in the survey. For most respondents the dominant energy expense is not electricity at all. It is combustion fuel for heat and cooking, which is also the source of nearly all the health damage and black carbon documented above. Households paying under about PKR 2,000 for electricity saw little reason to install solar to reduce a bill that was already low, yet the same households were open to replacing wood and gas cooking with electric alternatives. An intervention aimed at clean electricity alone would miss both the largest expense and the largest harm. Clean heat is where the leverage sits.

Table 4. Household and small-business survey responses, Skardu, Kachura, and Shigar

Respondent	Heating and cooking fuel	Fuel cost	Electricity bill	Household size	Would adopt
Residential 1	Own wood, gas for emergencies	150,000 per winter	2,500 to 3,000	11	Yes
Hotel 2	LPG, 60 kg per month	16,000 per month	2,500 to 3,000	11	Yes
Hotel 3	LPG, 60 kg per month	16,000 per month	2,500 to 3,000	11	Yes
Residential 4	Own wood and LPG	6,000	1,000 to 1,200	9	Yes
Residential 5	Own wood	1,200	1,000 to 1,200	6	No
Residential 6	Own wood and LPG	500 to 1,000	500 to 1,000	10	Yes
Residential 7	Own wood and LPG	4,000	500	6	Yes
Residential 8	Own wood and LPG	1,500	500	5	Yes

5.7. Willingness to Pay and Adoption Behaviour

Seven of the eight units surveyed said they would adopt solar or hybrid systems outright, and the eighth would adopt on instalments. Both hotels went further, offering to pay above the current per-unit tariff for supply that does not stop.

The condition attached to nearly every affirmative answer concerned payment structure rather than total cost. Households wanted low monthly instalments or flexible plans. They resisted large upfront outlays, and the one respondent who declined cited comfort with existing arrangements and traditional preference rather than price. Long load-shedding hours came up repeatedly as the reason for interest, which matches the outage effect reported by Bashir *et al.* [12]. Financing design, not the price of a panel, will decide adoption here.

Coding all eight responses against a set of adoption indicators gives the pattern shown in Fig. 2, reported as counts rather than percentages because a denominator of eight cannot support proportional inference. All eight respondents named solar as a preferred technology. Six were open to biomass or hybrid solar and biomass systems, and six reported chronic load shedding or winter supply failure. Four gave an explicit financing signal, split between two households wanting instalments and two businesses willing to pay a reliability premium. One household had been running solar for three years already, which is worth noting on its own: the technology is not unfamiliar here.

What emerges is a community that has largely decided it wants this and is waiting for terms it can meet.

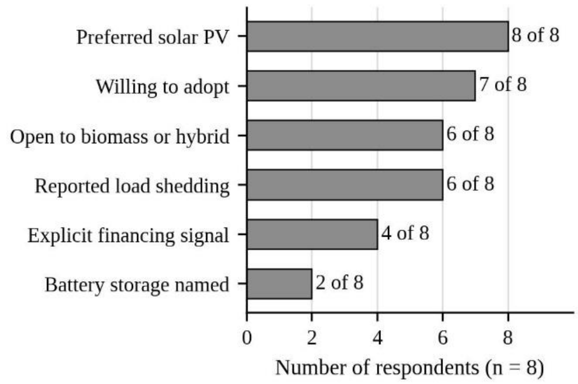

Fig. 2. Adoption readiness indicators coded from the survey responses

6. An Off-Grid Renewable Pathway

6.1. Distributed Generation and Storage Architecture

The evidence points toward generation built close to the load rather than delivered over distance. Several components suggest themselves, both from the survey and from what already stands on site.

Rooftop and community-scale photovoltaic (PV) generation can carry lighting and appliance demand. Where mini-hydro plants and their transmission lines already exist, panels can feed those lines instead of requiring new distribution, which removes a substantial slice of capital cost. Respondents in Kachura, where hydropower already supplies most demand, made exactly this point during the survey.

Storage is not optional here, because the demand peak falls in the evening and generation is weakest in winter, precisely when need is greatest. How storage is sold matters as much as how much of it there is. Respondents were far more receptive to batteries supplied and maintained by a provider against a service fee than to batteries bought outright, which is the Energy-as-a-Service (EaaS) model in practice.

Heat deserves separate treatment because it dominates both emissions and spending. The options that suit this valley are electric and solar thermal heating, including hydronic radiant systems, and hybrid arrangements pairing daytime solar thermal collection with efficient biomass backup for the coldest hours. None of these will perform without work on the building envelope, since insulation, sealing, and passive solar orientation reduce the demand before any system has to meet it. The carbon dioxide results in Section 5 add a requirement that is easy to overlook: every sealed, retrofitted room needs a controlled ventilation path, because tightening the envelope without one converts a particulate problem into an air-exchange problem. Solar food dehydration is worth adding as a productive use, because it also removes the smoke contamination that affects traditional open-air drying of apricots.

Together these components sit squarely within distributed generation, battery management, and energy access as the smart grid field understands them, and they remain deployable where no grid arrives.

6.2. Phased Deployment and Financing Roadmap

Deployment should follow capacity rather than ambition.

The immediate measures are inexpensive and largely behavioural. Improved and rocket cookstoves, passive insulation kits, sealing of obvious leakage points, and guidance on how to operate and vent a stove will reduce exposure and fuel use within a single season, and the workshop showed that this kind of intervention attracts local support quickly.

Over one to two years, training artisans and women's groups to retrofit stoves and homes and to assemble insulation and solar components moves the work into the local economy, which is what makes it maintainable. Solar water and space heating, pellet and gasifier stoves, and microhydro electrification for electric heaters belong in this phase.

Beyond that the larger investments become feasible: integrated housing retrofits with double glazing and passive solar design, community or district heating for clustered settlements, hybrid solar and biomass systems, and EaaS storage at scale.

Every stage runs into the barriers Nazir and Sharifi identified [2]. Financial constraint is answered directly by instalment and service-based models, which convert capital cost into an operating expense a household can absorb. Low awareness is answered by the participatory work described in Section 4. Neither answer is complete, but both can be acted on at community scale without waiting for national reform.

6.3 Techno-Economic Assessment

The architecture in Section 6.1 is only useful if it can be sized and priced, which is what this section does, using the site's own solar resource and the fuel expenditure recorded in Table 4.

Sizing follows the worst month rather than the annual average, because a system that fails in January is not a system. Long-term satellite data for the site give a specific photovoltaic yield of 1,558 kWh per installed kWp per year at an optimum tilt of 31 degrees [28]. The monthly distribution matters more than that annual total. January is the minimum month at 86.6 kWh/kWp, equivalent to 2.79 kWh/kWp per day, against 158.9 kWh/kWp in May. Winter output is therefore a little over half the summer figure once cold-cell efficiency is accounted for, and a system sized on annual averages would fail precisely when Skardu needs it.

We model a daily electrical load of 3.0 kWh, consistent with the appliances recorded in Table 4: lighting, refrigeration, and intermittent use of an iron, fan or heater. Taking the January yield, a battery roundtrip efficiency of 85% and module degradation of 0.7% per year [29], meeting that load in the final year of a 25-year economic life [30] requires an array of 1.5 kWp. One day of autonomy at an assumed 80% usable depth of discharge requires 4 kWh of storage.

Table 5 sets out the resulting costs. At PKR 120,000 per installed kW for photovoltaics [31] and PKR 52,000 per kWh for lithium iron phosphate storage, the capital cost is PKR 388,000, or about USD 1,400 at the State Bank of Pakistan rate of 9 September 2026 [32]. Annualising at a 10% real discount rate, the convention IRENA applies outside the OECD [30], and including one battery replacement at year 15, gives a levelised cost of PKR 55.4 per kWh. Across a plausible range of equipment costs and discount rates the figure spans PKR 43 to 72 per kWh.

Two features of that result deserve comment. The system is heavily oversized outside winter: worst-month sizing means the modelled load consumes only 47% of annual generation, which is an argument for aggregating households onto a shared asset or for adding a productive summer use such as the solar dehydration described in Section 6.1. And because Gilgit-Baltistan is supplied by its own utility rather than the national grid, and no per-unit tariff for that utility is published, a comparison against grid tariffs is not available to us. The comparison that matters here is with fuel.

That comparison is where the survey data earns its place. The capital cost of PKR 388,000 is equivalent to about 2.6 winters of the PKR 150,000 that one surveyed household reported spending on wood, and about 2.0 years of the PKR 16,000 per month that each surveyed hotel spends on liquefied petroleum gas. For the household reporting PKR 1,200 of fuel in a season, the same capital cost is equivalent to more than three centuries of fuel spending. Financed over five years at the State Bank policy rate of 11.5% [32], the system costs about PKR 8,500 per month.

This reproduces the survey result from the cost side, and it is the most useful thing the model does. The respondents who said yes are those whose fuel bills the system would displace within a few years. The one who declined reported the lowest fuel spend in the sample. Willingness to pay in Skardu is therefore not a matter of attitude toward technology but of whether the displaced expenditure is large enough to service an instalment, which is what Section 5.7 found by asking and what Section 6.3 now finds by costing.

Table 5. Techno-economic parameters and results for the modelled household system

Respondent	Heating and cooking fuel	Fuel cost
Specific yield, annual	1,558 kWh/kWp	Global Solar Atlas [28]
Specific yield, January (minimum month)	2.79 kWh/kWp per day	Global Solar Atlas [28]
Optimum array tilt	31 degrees	Global Solar Atlas [28]
Modelled daily load	3.0 kWh per day	Assumption, appliances in Table 4
Array size	1.5 kWp	Computed, end-of-life January basis
Storage size	4.0 kWh	Computed, one day autonomy at 80% depth of discharge
Battery round-trip efficiency	85%	NREL Annual Technology Baseline [29]
Module degradation	0.7% per year	NREL Annual Technology Baseline [29]
Photovoltaic economic life	25 years	IRENA [30]
Battery replacement interval	15 years	NREL Annual Technology Baseline [29]
Photovoltaic capital cost	PKR 120,000 per kW	IEEFA Pakistan [31]
Storage capital cost	PKR 52,000 per kWh	Pakistani market survey, 2026
Real discount rate	10%	IRENA convention outside the OECD [30]
Total capital cost	PKR 388,000 (USD 1,400)	Computed
Levelised cost of energy	PKR 388,000 (USD 1,400)	Computed
Sensitivity range	PKR 55.4 per kWh	Computed
Five-year instalment	PKR 43 to 72 per kWh	Computed at 11.5% [32]

7. Discussion

Energy access in Skardu is not one problem with three side effects. It is a single system whose failure registers at once in the lungs of residents, in the valley's air, on the surface of nearby glaciers, and in household budgets.

That has a practical consequence for anyone designing an intervention. Distributing improved stoves will lower indoor concentrations, but it cannot clear a valley under inversion or halt deposition on ice. Supplying clean electricity without addressing heating reaches only the smaller expense and the smaller share of emissions. Only a system coupling distributed generation and storage with clean heat reaches all three at once, which is the argument this paper makes.

The device-resolved measurements sharpen that argument in two ways. The fuel gradient is large, which means fuel switching delivers real and immediate exposure reduction rather than marginal gains. The carbon dioxide record shows that fuel switching is nonetheless insufficient on its own, because the cleanest fuel measured produced the worst ventilation signal. Interventions that treat the fuel and the building envelope as separate problems will underdeliver on both.

The Pamirs case supports the overall direction and warns against optimism about pace. Sadik-Zada *et al.* [11] recorded substantial income and education gains after electrification alongside incomplete fuel switching driven by habit and taste. Our survey shows the same texture: near-universal willingness, with one household declining for reasons no tariff will change. Technology and participatory engagement have to travel together. Meanwhile the national picture [1, 2] suggests centralised modernisation will remain constrained by structural and financial barriers for some time, which strengthens rather than weakens the case for community-scale off-grid systems now.

The survey's eight respondents also need setting against the scale of the community they are drawn from.

The Pakistan Bureau of Statistics does not publish district-level household counts for Gilgit-Baltistan, so no measured denominator exists. Skardu District's 2023 census population is reported by the regional Planning and Development Department as 278,885 [33], and the mean household size recorded for Gilgit-Baltistan by the 2016 to 2017 Multiple Indicator Cluster Survey is 7.7 persons [13], which together imply on the order of 36,000 households. Eight units is therefore a very small fraction of one percent of the district. We report the adoption indicators in Fig. 2 as counts for that reason, and no proportion in this paper should be read as an estimate of a population share. What the survey supports is a description of expenditure and of the conditions attached to willingness, and both are independently reproduced by the cost model in Section 6.3.

Several limitations bound these conclusions. The air quality record covers one heating season, and the outdoor record covers a single month within it, so variability beyond that window is unmeasured. That month was also not meteorologically ordinary, and we state this rather than claim typicality. The Pakistan Meteorological Department records November 2023 as the eighth warmest and December 2023 as the sixth warmest in a 63-year national series, with anomalies of 1.24 and +1.59 °C against the 1961 to 1990 normal, and December rainfall 92% below normal nationally and 97% below normal in Gilgit-Baltistan, the fourth driest December in that series [34]. The department characterises December 2023 as dominated by dry continental air and dense fog. A strong El Nino was active, with an Oceanic Nino Index of +1.90 for the October to December season [35], although the wet winter response that usually accompanies it over Pakistan did not materialise. A dry, stable, fog-prone December suppresses ventilation and favours accumulation, so the concentrations reported here are more likely to sit above than below what an ordinary December would produce. The indoor measurements are drawn from a small number of monitored rooms and are reported as observed ranges with the sample count stated in Table 1. Low-cost optical sensors carry inherent uncertainty even after the checks described in Section 4.1, and published evaluations of this sensor family report absolute errors that grow with relative humidity and vary in sign between studies [15], [16]. The glacier figures are modelled from literature parameters rather than measured from snow cores. The cost model in Section 6.3 rests on a modelled load and on market cost data rather than audited project accounts, and no official Pakistani capital cost benchmark for solar photovoltaics is published, which is why we report a sensitivity range rather than a single figure. The survey's eight respondents indicate expenditure and preference; they do not represent a population.

The obvious next steps follow from those limits: a full heating-season record across a larger number of instrumented homes with gravimetric co-location, a larger willingness-to-pay study anchored to explicit price points, and a techno-economic sizing with levelised cost of energy for the architecture proposed in Section 6.

8. Conclusion

We set out to establish what energy poverty costs a high-altitude off-grid community, and whether an off-grid renewable system could plausibly replace what people currently burn.

The cost is measurable and large. Indoor $PM_{2.5}$ reached 463 µg/m^3 with a wood stove and 382 µg/m^3 with cow dung, exceeding the World Health Organization 24-hour guideline by a factor of 20 to 31. The room heated by a gas appliance was the cleanest space monitored by day, at 48 to 149 µg/m3, and rose to about 405 µg/m3 during the evening peak, when carbon dioxide fell and outdoor air entered. Indoor carbon dioxide reached 4,711 ppm, which shows that these rooms are effectively unventilated. Outdoor daily AQI peaked at 467, produced by household heating in a town with no industry. Modelled black carbon deposition adds an estimated 1 to 3 mm of water-equivalent melt per day on nearby ice. Fuel bills reached PKR 150,000 in one winter. These are not separate findings but readings of the same system. All of the concentration figures rest on low-cost optical sensors, and we present them throughout as robust indicators of relative magnitude and of the gradient between configurations rather than as gravimetric reference-grade absolutes.

The replacement is technically available, socially acceptable, and now costed. Rooftop and community solar, storage delivered as a service, and clean electric or solar thermal heat address all of these costs together, and the households surveyed want them. Sized on January irradiance, a 1.5 kWp array with 4 kWh of storage meets a 3 kWh daily load at a levelised cost near PKR 55 per kWh, for a capital outlay recoverable within about two to three winters of the fuel spend the highest-spending surveyed households already report. What those households will not accept is a large upfront payment, which makes financing structure the binding constraint rather than technology or willingness.

The contribution here is the pairing: a device-resolved, multidimensional baseline and demand-side evidence drawn from the same community, which is what an energy access plan for a cold off-grid valley actually requires. The approach transfers readily to comparable settings across the ASEAN region and the wider Himalayan belt, where similar valleys face similar winters. What remains is to size the system and price it properly.

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