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Decentralised Electric Power Delivery for Rural Electrification in Pakistan

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Abstract:

The paper evaluates solar powered microgrids as a candidate solution for rural electrification in Pakistan where over 51 million people still live off-grid. Decentralised microgrids have scalable architecture and can significantly reduce the cost of providing higher levels of services efficiently through energy and cost sharing. We show the viability of such a system in Pakistan, by reporting the results of willingness to pay surveys from off-grid villages in the Multan district of south Punjab. We find that on average households are willing to pay PKR.187 for high quality lighting and almost double of that for the addition of a fan. This demand can be met through decentralised microgrids that can be commercially viable with minimal government support. Policy recommendations, in particular policy geared towards enabling private parties to setup microgrids are also presented.

1. Introduction

Access to electricity, even simply the provision of high quality lighting alone, has been shown to increase productivity and provide opportunities for economic development. According to the International Energy Agency (IEA), more than 440 million occupants in developing Asia (China, India, Pakistan and Bangladesh) and further 580 million in Africa have no access to any form of electricity [1]. Most of those who live *off-grid* do not have a choice in this regard, and must rely on unreliable and even unhealthy alternatives, like kerosene oil with many documented ill-effects [2, 3]. The major source of electricity i.e. the national grid is unviable for many of these isolated communities, as the large upfront costs of electrification through the national grid makes expansion prohibitively expensive for governments in developing countries [4, 5]. Therefore, a paradigm shift towards powering these villages through low cost (and consequently low-power) distributed renewable resources such as solar photovoltaics (PV) has been seen in recent years [5-8].

A recent innovation in the field of decentralized generation is the solar direct current (DC) microgrid [9-11]. A microgrid is generally built around a centralised solar generation mechanism that provides multiple households with electricity through a DC cable network. While requiring up-front setup costs, a microgrid allows the provision of *basic electrification* (defined as high quality lighting and charging a mobile phone), to multiple households in a single community at a significantly lower

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long run cost than traditional power provision mechanisms. It is also a promising alternative to standalone solar systems and fossil fuel generation, as it presents a low cost, sustainable and green alternative.

Prominent practical implementations of microgrids include setups in India, China and Africa [12-14]. The most common commercial scale implementation is the Mera Gao Power (MGP) project in India which provides 5W of DC electricity, enough to alternately power an LED light and a mobile-phone charging point, to each subscribing household in a village for about 8-hrs per day. MGP has reportedly connected over 10,000 households spread across 400 villages [13, 15]. In 2012, Uttar Pradesh and Renewable Energy Development Agency, installed 1 kW DC microgrids in 11 districts covering around 4,000 houses [16]. Other, recent successfully deployments include those in Cameroon and Papua New Guinea, that typically provide up to 10W of power per household for 8-hr daily operation [17]. Other small container based solar solutions on 12V and 24V are also being readily utilized in Africa [18-20]. However, none of these systems provide a 24/7 supply to rural communities due to large costs required for generation and, in particular, storage requirements [21].

Microgrids then have been a successful solution for providing *basic* electrification in off-grid communities, however we have not seen an influx of these in Pakistan [22]. Pakistan is the sixth largest nation in the world with over 31 million people (15% of the population) living offgrid with no access to electricity [23]. Given Pakistan's well documented power crisis and its historical similarities with India, which is itself at the forefront of the microgrid movement [15, 23, 24], the lack of microgrids in the country is quite surprising. In this paper, we establish that there is both a demand for electrification in off-grid areas, and this demand can be met through new decentralised solar microgrid architectures. We find that not only does demand exist for basic electrification; there is significant demand for services beyond high quality light and mobile charging. Further, we evaluate standalone solar PV systems, conventional microgrids and new decentralised microgrids (an innovative new architecture that can meet this more sophisticated demand [11]) from their viability and long term levelised costs perspective. Finally, we make policy recommendations based on our findings, in particular, the need for governments to provide an enabling environment for private parties to provide electrification through the use of microgirds. This can be done by introducing more flexibility in the law governing the generation and distribution of electricity in the country, which is the largest hurdle in the adoption of microgrids in Pakistan.

2. Demand for electrification

To ascertain the demand for micro-grids, we conducted surveys in off-grid rural communities in the Multan district of the Punjab province. These areas are characterised by "bad line coverage", due to their proximity to the Chenab River, whose regular flooding, making reliable long term connections to the national grid costly.

Data from the survey of 140 households highlights the need for electrification beyond just high quality lighting. In the sections that follow, we describe the data, provide summary statistics for socio-economic make-up of our sample and establish our main demand side results, namely, that there is considerable demand for electrification in the region, beyond just high quality lighting. In later sections we show how this demand cannot be met by traditional microgrids, but can be met through the use of decentralised microgrids.

2.1 Survey and data

A household census was carried out across 7 villages in the Multan district of Punjab. The surveys covered all 140 households in the area that were designated as off-grid, i.e. they are not covered by the national electricity grid. Other than basic household characteristics, the survey elicited willingness to pay for different bundles of electricity services, to gauge the demand for such services.

Table 2.1 provides summary statistics for the socio-economic indicators of the households in our sample. As can be seem from the table, households in our sample are generally low income, with an average per capita income of PKR.2725.2, which is approximately USD 25 per month, or less than a dollar a day per person. A possible caveat, as highlighted by past literature, is that self-reported income is typically underreported [25, 26]. However, we find that the reported expenditure on food and other general expenses, which are typically used as proxies for income, closely match the results for income. Similarly, instances for meat and fruit consumption are also low, coming out to about once a week for both on average. An interesting result is the generally high levels of school attendance reported by our sample (of the 104 households who answered the question, 80 reported their children attended school regularly).

Variable	**Mean**	**Standard Deviation**	**Number of observations**	**Median**	**10th Percentile**	**90th Percentile**
Household size	6.72	2.99	140	6	3	10
Number of children	3.02	2.09	139	3	0	6
Monthly income (PKR)	14647.48	13753.98	140	10000	5000	30000
Monthly income per capita (PKR)	2366.62	3576.16	140	1464.27	600	5000
Monthly Expenditure on Food (PKR)	9466.43	7124.80	140	8000	20000	4000
Monthly expenditure on food per capita (PKR)	1958.64	1325.23	140	1309.52	600	3000
Monthly expenditure on schooling (PKR)	1606.60	2429.002	106	1000	0	3000
Monthly Meat consumption (Average number of times a month)	4.69	3.30	139	4	0	8
Fruit consumption (Average number of times a month)	5.34	3.51	140	4	4	8

Table 2.1: Household Characteristics. Any person under the age of 15 is defined as a child.

In addition to self-reported data on household characteristics, we collected information on the type of house. We found that the vast majority of houses (92, or 66.2%) had temporary foundations (mud based houses), locally referred to as *kacha* houses (loosely, ad hoc). The remaining houses (bar 1 *pakka* or permanent house) were a mixture of modern building materials and temporary foundations, further strengthening the income story from Table 2.1. This should however not be surprising. House location, vis-à-vis grid electrification, should be considered a function of household income and wealth, as property rates in localities with easy access to basic utilities would be higher.

	Level of service	**Prices**		
		Price plan 1	Price plan 2	Price plan 3
1	24/7 provision of high quality light (3 LED lights), and a mobile charging point.	150	250	450
2	Services in Bundle 1 and a Fan.	300	500	900
3	Services in Bundle 2 and shared communal load (water pump).	450	750	1050

Table 2.2: Services offered and their prices by plan (All prices in PKR per month)

Finally, the survey elicited whether households would be willing to pay for three different levels of electricity service, provided through microgrids. Levels of service were chosen to replicate services provided by traditional microgrids, such as Mera Gao Power, and those made available through the use of decentralised microgrids architecture.

The prices at which these services were offered were randomised between three rate plans, which presented increasing prices for each level of service. Due to the close proximity of households inside each village, plans were randomly allocated at the village level, instead of the household level. Table 2.2 provides details of the level of services and their respective prices per month under each price plan. If respondents refused services at the stated price, they were asked to report the maximum price at which they would accept services.

2.2 Results

Table 2.3 reports prices respondents were willing to pay for services, both overall and separated by price plan offered. As aforementioned, they could either accept a price from a randomised price plan or reject and report their own maximum. Note that these are by construction truncated values for willingness to pay, as any price reported after rejecting the quoted price has to be lower than the initial price offered by the enumerator.

We find that those who rejected Price Plan 2, reported willingness to pay very close to those offered in Plan 1, though they are statistically lower for highest level of service. Finally, the reported willingness to pay under Price Plan 3 suggests the effects of anchoring based on the initial price quoted. All prices are statistically significant, suggesting a clear demand for services at all levels, regardless of the price plan used by the enumerator.

Not only is demand for the level of services significant in our sample villages, we also find that demand for higher levels of service is significantly higher than for basic electrification. Table 2.4 reports the absolute and relative difference in prices respondents reported they were willing to pay with respect to the base level of electrification (lights only).

		Average Price (standard error)		
	Number of HH	Lights Only	Lights and Fan	Lights, fan and communal load
Overall	122[3]	187.05 (9.80)	340.16 (16.69)	434.59 (17.37)
Price plan 1[4]	22	150 (0)	300 (0)	450 (0)
Price plan 2	56	153.04 (6.91)	293.75 (12.81)	379.82 (12.29)
Price Plan 3	44	248.86 (23.08)	419.32 (40.97)	496.6 (43.90)

Table 2.3: Average prices willing to be paid for each level of service

We find that there is significant difference for all services beyond those provided by traditional microgrids (lights and mobile charging). Both the absolute and relative differences significant statistically and practically. Households are willing to pay almost twice as much for the addition of a fan, and about 2.5 times more for both a fan and communal load.

Additionally, the marginal change between the two highest levels of service is also found to be significant, with household willing to pay and additional Rs. 94 for a shared village water pump (communal load).

	Number of Observations	**Absolute difference**	**Relative Difference**
Lights and Fan v. Lights	122	153.12 (11.81)	1.97 (0.67)
Lights, fan and communal load vs. Lights	120	247.54 (11.74)	2.57 (0.07)

Table 2.4: Relative and absolute difference in reported prices with respect to base plan (lights only). Standard error in parenthesis. Absolute difference is the arithmetic difference in prices of two packages ($P_y - P_x$), while relative difference is their ration (P_y/P_x).

Given the richness of our data, we are also able to ascertain the determinant of demand for households in our sample. Table 2.5 reports the results of our fully specified model, where we control for respondent, household and village level characteristics, as well as for reference dependence, by controlling for the price plan that was offered. Finally, villages in our sample were both relatively small and geographically clustered together. In effect, there were two clusters, with villages inside clusters separated from each other by a couple of acres. Our specification also controls for any cluster effects.

We find that for households in our sample, the willingness to pay varies with income, number of household members currently employed and by standard of living indicators. Interestingly, we find that regardless of the level of service offered, the willingness to pay is decreasing in monthly income, though it decreases at a decreasing rate. Similarly, increase in the consumption of fruit also lowers willingness to pay across the board. These results are counter intuitive; as we use fruit comsumption as a proxy for standard of living. However, this may suggest

[3] A village in the survey refused to answer questions regarding service through solar panels. The village was expecting a grid connection in the coming month, and interpreted the solar service as an alternative.
[4]All respondents in Village 2 accepted the quoted prices under plan 1, yielding a standard error of 0.

that those with higher standard of living have more readily available access to alternative sources of energy.[5]

We also find that respondents with more years of education were more open to the use of solar technology, reflected in their higher willingness to pay. This suggests the need for familiarity with new technology, and the need for demonstrations and free trials are part of any on the ground intervention. Similarly, we can confirm the existence of anchoring by price plan, as households offered the highest price plan (3), reported higher willingness to pay, both practically and statistically.

Willingness to Pay (Rs.)	(1) Lights	(2) Lights and Fan	(3) Lights, Fan and Communal Load
Education	7.015**	10.21*	10.78*
	(3.133)	(5.996)	(6.338)
Number of members currently employed	22.14**	-21.08	-11.12
	(9.085)	(30.93)	(28.48)
Monthly HH income (Rs. 1000)	-6.325***	-9.533**	-12.94***
	(1.795)	(3.919)	(3.826)
Monthly HH income squared (Rs. 1000)	0.0863***	0.162***	0.228***
	(0.0280)	(0.0546)	(0.0546)
Average weekly fruit consumption	-42.27**	-64.88*	-75.03*
	(18.38)	(34.98)	(43.33)
Village is in Cluster 2	-112.9**	-182.3	-314.7**
	(45.54)	(164.4)	(157.5)
Price Plan 2 was offered	-67.34***	-122.4***	-208.4***
	(17.97)	(34.01)	(36.74)
Price Plan 3 was offered	95.60***	115.7***	31.95
	(21.69)	(33.34)	(35.05)
Constant	389.9***	633.9***	949.1***
	(74.24)	(188.0)	(185.2)
Observations	108	108	108
R-squared	0.504	0.369	0.429

Table 2.5: Multivariate analysis of determinants of willing to pay, including controls for respondent and household characteristics.[6] Base is a household in Cluster 1, with a *kacha* structure, offered price plan 1. Robust standard errors in parentheses; ∗∗∗p < 001, ∗∗p < 005, ∗p <0.1.

Finally, we find evidence of cluster effects, as villages in our base cluster, on average, reported significantly higher willingness to pay than those in cluster 2. Given the small size of village clusters that are off-grid, this finding suggests that any intervention first account for geographical

[5] Our survey instrument also asked respondents to list their alternative sources of energy, however we found that nearly all respondents were unwilling to volunteer this information.

[6] In addition to income and children's study patterns, controls were added for the house's physical structure, HH size, number of children (under 15 years of age) and the consumption of fruits and meat. Furthermore, in addition to education level of respondent, we control for respondent age and whether he was the household head. Income of respondent is highly correlated with HH income and so was dropped.

variation. Table 2.6 calculates the average willingness to pay in each cluster and reports the difference. As can be seen, while the willingness to pay in both clusters are practically and statistically significant, so is the difference.

		Average Price (standard error)		
	Number of HH	Lights Only	Lights and Fan	Lights, fan and communal load
Cluster 1	29	242.07 (31.62)	429.31 (57.21)	562.76 (60.09)
Cluster 2	91	171.43 (7.66)	315.38 (11.66)	398.35 (10.05)
Difference (Cluster 1 – Cluster 2)	-	70.64 (32.54)	113.92 (58.38)	164.41 (60.92)

Table 2.6: Average willingness to pay by cluster, and average difference across clusters, with standard errors reported in parenthesis.

3 Viable supply through decentralised microgrids

Current microgrid technologies for low-cost rural electrification deployed throughout the world rely on low voltage DC distribution. These largely self-sustained implementations typically allow for up to 8 hrs of electricity provisions per day [27]. The most prominent implementation of low-cost rural electrification is the Mera Gao Power (MGP) project in India. As discussed, MGP operates an estimated 400 microgrids that provide 5W of DC electricity for 8 hours a day to each of it 10,000 subscribing households [13, 15].

Scaling-up such a system to provide 24-hour service is impractical due to the higher costs associated with higher power generation as well as storage capacity. In addition, with low voltage distribution, there are significant line losses which limit both the deployment radius and maximum power provision of the system, and in turn limit the size of the system. It is for this reason that almost all sustainable microgrids offer only basic electrification (up to 10W per household) for few hours a day.

In order to analyse this problem from an implementation perspective, we divide the technology available for rural electrification into three categories, i.e.

1. Standalone or isolated solar home systems (No power sharing)
2. Traditional low voltage microgrids (central generation e.g. Mera Gao Power)
3. New distributed microgrid (with decentralised resources i.e. decentralised generation and/or storage)

The general schematic diagram for standalone implementation is shown in Fig. 3.1. Standalone systems are generally suboptimal due to generation and consumption profile for most rural communities. Solar panels produce most power around noon time whereas the consumption is likely to be higher in the early mornings and late evenings or nights. Therefore, large storage is required for operation which makes these systems very costly upfront [28, 29].

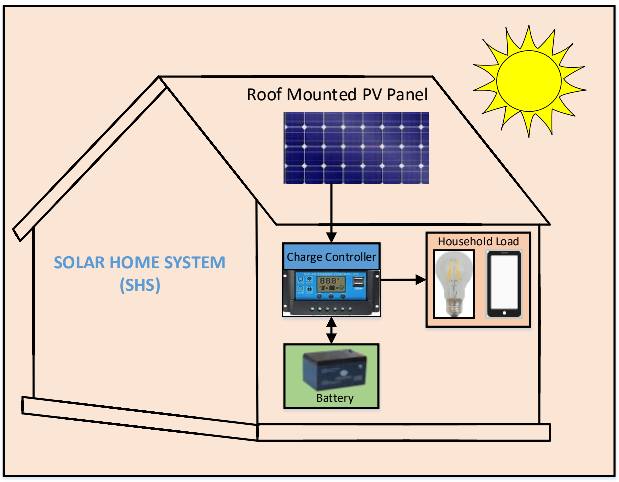

Fig. 3.1. Schematic Diagram for Standalone/Solar Home System

Centralised microgrid implementations (Fig. 3.2), on the other hand, are more energy efficient than standalone systems due to resource sharing capabilities. Subscribers share resources that are both generated and stored at a central facility. Some flexibility, gained through diverse usage across households, yields smaller sizing of the overall system with equivalent power delivery when compared to standalone systems.

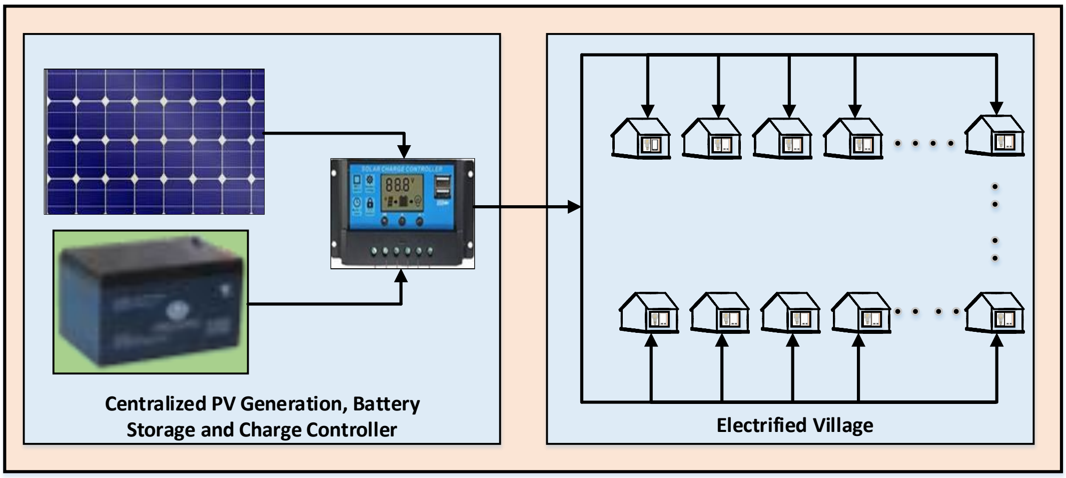

Fig. 3.2. Schematic Diagram for Microgrid based Centralized Model of Rural Electrification

The low voltage distribution (12V/24V) typically used by such systems limit both higher power load provision and larger grid sizes. The primary deterrent to higher provisions and lack of scalability are the considerable line losses at low voltages. Furthermore, even if efficiencies are accounted for, the addition of new users on the microgrid is not as simple as increasing power generation and storage. Mismatch in panel generation and storage that is exasperated with age of the system, makes the system rigid in terms of operational expansion.

An alternative to traditional microgrids are decentralized microgrids which can cater many of the issues with traditional microgrids. Decentralised microgrid systems rely on the distribution of resources in terms of generation as well as storage where most of the power produced is consumed locally with only surplus power shared between neighbours, and allow for the possibility of powering a shared communal load. Such a system has the inherent tendency of resource sharing to extract benefits of usage diversity thereby lowering wastage and increasing efficiency. The extra power from each household may also be aggregated to run a community load, e.g. a water filtration plant, medical equipment of a local hospital or computing load of a school. Some decentralised microgrids [8, 30] rely on communication among the distributed resources which requires an extra sensing, monitoring and communication layer, which increases the cost and complexity of the system. From a rural electrification perspective, such a high cost system may not economically viable. Some newer decentralized architectures having distributed resources (generation as well as storage) allow higher resource utilization along with the capability to aggregate individual resources for powering a high power community loads (Fig. 3.3) [11].

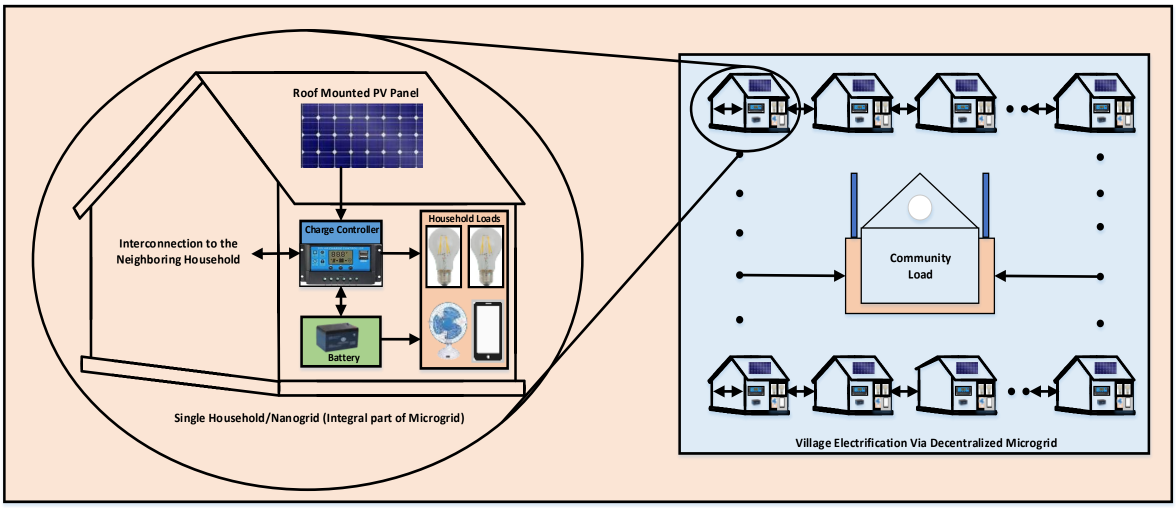

Fig. 3.3. Schematic diagram of proposed decentralised solar microgrid

Given that the average willingness to pay for basic electrification in our sample is around PKR.187 for basic electrification and PKR.340 for the additional provision of a fan, we need to ensure the economic viability of the proposed decentralized scheme in comparison with current systems. It is therefore important to analyse all three systems in terms of their cost and ensure that they present viable paths to electrification for off grid communities.

Consider then the cost evaluation problem for rural electrification. For a typical village with *N* households and allowable power provision of P_h watts per household for *T* hours and a communal load of P_c *watts* for *t* hours, the total number of required energy units at the output E_O of system is given by the following equation.

$$E_o = (NP_h T)U_d + P_c t \ , \tag{1}$$

Where, U_d is the usage diversity factor that captures the inter-household usage diversity in energy expenditure at any given time. Intuitively, it captures the fact that the power demand of each household will be less than or equal to allowable provision and will be different from other households in the village.

It is typically assumed that $U_d < 1$, i.e. on average households are consuming below their allowed provision. For example, it is reasonable to assume from a design perspective that in the day time when sunlight is available, lighting load at each household will be reduced. Similarly, in winters the fan loads will be reduced due to seasonal variation in temperature and associated cooling requirements. Therefore, panel requirements are reduced accordingly and are quantified in Equation 1. The capability to extract the benefit of usage diversity is precisely the reason microgrids are more efficient that standalone systems.

Given the energy requirement E_0 of a system, system characteristics such as solar PV panel sizing required to produce the requisite amount of power must be calculated. These must take into account the incident irradiance, effect of temperature degradation and various losses including wiring losses, converter losses, and storage losses during charging/discharging cycle losses.

To account for various energy losses and degradation in a system, the amount of energy needed to be produced, E_p, is given by

$$E_P = \frac{E_0}{\eta_T \eta_B \eta_C \eta_D} . \tag{2}$$

Where, η_T, η_B, η_C and η_D are degradations in efficiency due to temperature, storage (or battery) inefficiency, convertor inefficiency and line losses, respectively. The resulting panel size P_{PV} needed at per household can be expressed as

$$P_{PV} = \frac{E_p}{\bar{E}N} , \tag{3}$$

where, $\bar{E}$ are the peak sun hours for the particular region. Similarly, for first order cost calculation model for a battery system, the battery energy capacity E_B is determined by the total energy that battery has to supply when the sun is not available along with the extra energy that is dissipated during charging/discharging. Moreover, to extend the battery life, generally there is a limit on minimum discharging state SOC_{min} (%), which again tends to increase the required battery capacity. The overall battery requirement for a microgrid then is

$$E_B = \frac{\left(\left(24 - \bar{E}\right)P_h\right)\left(1 + SOC_{\min}\right)}{N\eta_B} . \tag{4}$$

In addition to storage and solar panel costs, there are other costs which include the cost of converters, system protection equipment and conductor (wiring) length. The price of converters is generally proportional to their power processing requirements, loading levels and current carrying capacity. Therefore, for simplicity, it can be taken as a fixed percentage, λ_c, of the total cost of PV panel. Similarly, the cost of protection is proportional to the power loading level and short circuit current capacity, therefore, in the current analysis it can be taken as a fixed percentage as well (λ_p). Finally, the cost of total conductor length (l) is given by C_3 (PKR/m).

Considering PV panel cost as C_1 (PKR/watt) and battery cost as C_2 (PKR/*watt-hour*), total system upfront cost is given by

$$C_U = \left(\left(1 + \lambda_C\right)\left(C_1 P_{PV}\right) + \left(C_2 E_B\right) + \left(lC_3\right)\right) * \left(1 + \lambda_P\right). \tag{5}$$

Generally, life time of a solar panel is *25* years, while the life time of battery can be taken as N_B years and life time of power electronic converters is given by N_C years. Therefore, for a typical 25 year system, the operation and maintenance cost, along with the number of battery and power converters replacement is calculated and added with the capital cost to find the overall lifetime cost of the system. The total lifetime cost C_{LT} of the system is given by

$$C_{LT} = C_U + \left(\left(\frac{25}{N_B} - 1 \right) \left(\left(C_2 E_B \right) \right) + \left(\frac{25}{N_c} - 1 \right) C_1 P_{PV} \lambda_C \right) \left(1 + \lambda_P \right). \qquad (6)$$

Further, it is important to evaluate the effective levelized cost of electricity, L(PKR/kWh) of the system, given by equation (7), which effectively calculates the cost of each unit produced by the microgrid over its 25 year operation in comparison to its lifecycle costs.

$$LCOE = \frac{C_{LT}}{E_O(365)(1000)(25)} \qquad (7)$$

Where, E_O is the energy produced per day which is multiplied by 365 (days in a year) and 25 (operational lifetime of the system). 1000 (in the denominator) gives LCOE in price per kWh as kWh is standard unit for electricity production/consumption.

The presented cost model is applied for the electrification of a typical village having 40 houses, 30W rated power at each house with ± 100% flexibility in power provision i.e. each house may consume up to 60W (double of its rated power) of electricity, or may sell 30W of electricity at a given time. The rated power provisioning is in accordance with the market availability of DC loads with three lighting bulbs (~4W each), one DC fan (~14 W) and one mobile charging unit (~4 W).

Similarly, for the village under analysis a communal load of up to 500W is considered for water filtration plant/pump for drinking purposes. The household operation is for 24 hours while communal load operation is considered for 6 hours per day. The peak sun shine hours ($\bar{E}$) for the typical village are assumed to be 6 hours per day (6 hours of standard daylight on average over the year).

The proposed first-order cost analysis model is applied on the village with specifications discussed above to calculate system sizing requirements and associated costs. Usage diversity factor is considered 0.3, which approximates lack of simultaneous loading for all households at all the time. The costs are taken as followings:

- PV panel price C_1=80 PKR/kWp [31, 32],
- battery price C_2=105 PKR/Wh [33] (Lead acid battery),
- distribution conductor cost for the village is PKR.50000 [34] and converter cost factor λ_C=0.3 and protection cost factor λ_P = 0.05 [35].

Therefore, considering all these factors, LCOE, along with flat rate tariff plan for the proposed and existing schemes of electrification is calculated over 25 year project life. For 6 years ROI plan, one battery replacement is considered, for 9 years ROI plan, one battery and one charge controller replacement is considered, while for 12 years ROI plan 2 batteries and one charge controller replacement is considered. Table 3.1 presents the estimated costs of all three topologies including communal loads and compares them to alternative implementations. Kindly note that these are typical costs and the prices may vary from one region to another. There may well be additional costs for some newer aspects of efficient power processing (power electronics) in distributed microgrids. Solar panels, storage and distribution prices used are standard wholesaler's rates, correct for the month of December 2017.

Level of Service	Load per house (24/7 provision to subscribers)	Capital Cost (PKR)	Capital + 25 years O&M Cost (PKR)	Subscription Charges Per user per Month for payback in (PKR/Month)			
				3 years	6 years	9 years	12 years
Tradition low voltage microgrid (e.g Mera Gao Power)	1 light and mobile phone charging unit (5W).	211700	477500	147	91	66	62
Decentralized Microgrid	3 Lights, 1 fan, charging unit (30W)	956300	2614900	665	445	330	270
	3 Lights, 1 fan, charging unit and Communal load (30W +500W)	1000000	2678700	695	473	350	325
Standalone Production and Consumption (No grid)	3 Lights, 1 fan, charging unit (30W)	1082800	2930000	750	515	350	330
	3 Lights, 1 fan, charging unit and Communal load (30W + 500W)	1165800	3130400	810	560	400	380

Table 3.1: Estimated cost of competing solar generation implementations for a system of 40 households (Average market costs for Dec 2017)

Our calculations show that solar power, in particular decentralized microgrids, present a viable alternative to grid electricity even for loads beyond high quality light. For nominal fixed monthly prices, consumers can be provided with multiple lights and a fan. Given the average willingness to pay results from households in our survey (Table 2.5), they system can break even within 9 years for a system with lights and fans. While this may not be as attractive to entrepreneurs, it offers a low cost system to governments, who can with very low levels of subsidies, make this an enticing proposition for local entrepreneurs. Table 3.2 reports the years to break even for entrepreneurs based on different levels of government subsidies, assuming monthly subscription charges well below the average willingness to pay (PKR. 250 for lights and fan and PKR. 350 with a communal load).

Level of Service	Number of years to break even with Government subsidy on upfront cost			
	25%	50%	75%	100%
Lights and Fan Upfront cost =956300PKR	10	7	2	<1
Lights Fan and Communal Load Upfront cost =1000000	7	6	2	<1

Table 3.2: Years to break even while charging PKR 250 for lights and fan while charging PKR 350 for lights, fan and communal load

Finally, a major component to the cost of any solar system is the cost of storage. Batteries are both expensive, have short life spans and are inefficient. As an example, for a case of a decentralized microgrid, we show that the cost of storage highly dominates the overall cost of the system in its lifespan of 25 years (Fig. 3), at current market prices. However, recent developments in battery technology suggest that the overall cost of such a system is likely to come down in future [36].

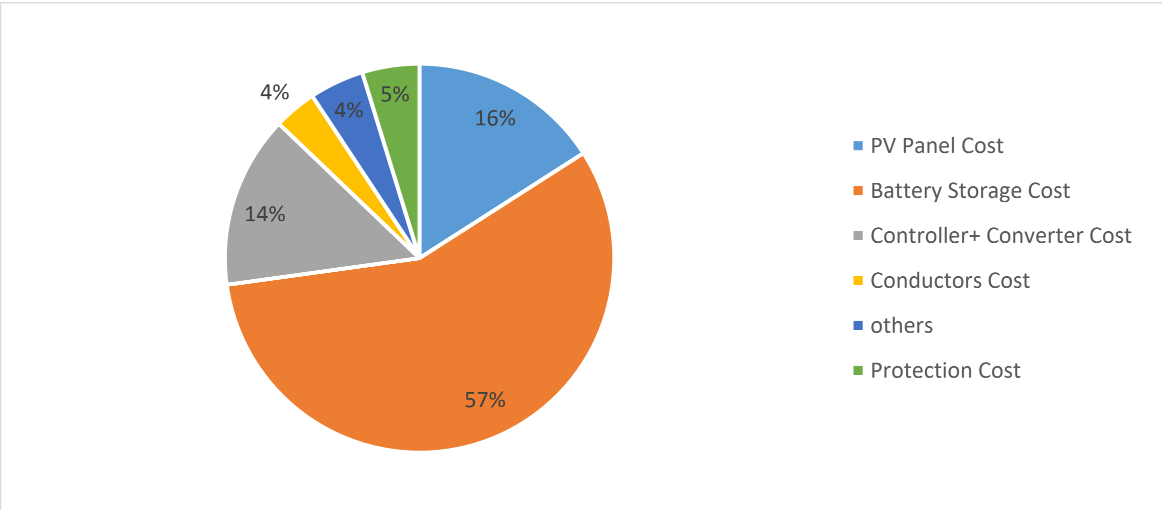

Fig. 3.4 Life Time (25 years) Operation Cost Break-up of a Distributed Microgrid.

4 Conclusion and Policy recommendations

4.1 Overall Conclusions and Future Research

The current study is part of a broader research agenda which seeks to ascertain the demand for electrification in rural off grid regions of Pakistan, and design and implements systems that can meet these needs in a cost effective manner. Our findings indicate that decentralised solar microgrids present a promising route to rural electrification, especially in areas where grid expansion may be prohibitively expensive. They have the capacity and scalability to provide electricity beyond those offered by tradition microgrids. In countries like Pakistan, that are already facing major crises in supply, they present a low cost solution to not just the distribution problem, but also the problem of generation.

The next steps in this agenda would be the roll out pilots of decentralised microgrids in the surveyed areas, and to follow that up with full randomised control trial across multiple villages to pin down the revealed demand for electrification, and determine what characteristics and interventions increase or decrease willingness to pay. Another natural area for expansion would be to study the appropriateness of micro grids as a source of back up electricity in on grid areas, experiencing high number of rolling black outs.

4.2 Broader policy implications

Decentralised microgrids present a low cost and sustainable solution to the problem of rural electrification. They also provide an opportunity for local entrepreneurs and communities as a whole to lift themselves out of energy poverty. The only hurdle is the relatively high upfront cost of such a system, which requires very long periods of time before investors can break even.

In such a situation, we recommend that governments play a more active role in helping finance microgrids through possible subsidies and tax breaks. Helping small entrepreneurs and communities through a subsidies and technical knowhow, or collaborating with larger players through public-private partnership can yield a sustainable long term solution to the needs of their populations, without the need to invest in large and significantly more expensive grid based solutions.

4.3 Policy implications for Pakistan

We find that microgrids present a viable solution to the rural electrification problem in Pakistan. According to our estimates of both demand and cost, we find that even traditional microgrid setups would fare well in Pakistan. The lack of pre-existing implementations may then be attributed to the inflexible nature of laws governing electricity generation and distribution in the country. A review of the current legal framework shows that it is illegal for private parties to sell electricity to other private agents.[7] Exceptions to the law exist, but do not apply to a typical microgrid setup. A private entity cannot set up a distribution system for a rural community to sell electricity without a prior license for generation, as well as approval from the regional distribution company. The system is in its current formulation too complicated for local entrepreneurs or even larger entities to be able to operate microgrids at the community level.

In light of our findings and the current policy environment in Pakistan, we recommend that Pakistan provide an enabling environment to entrepreneurs and organisations that wish to provide rural electrification through renewable energy. In the case of Pakistan, we recommend that the law be altered to allow private parties to generate and distribute electricity through renewable sources up to 100KW in off-grid and bad grid areas at a village level.

Furthermore, such entities should require a single licence from a local authority (e.g the Union Council), instead of the multiple licences required from multiple parties, at various levels of government. In the current setup, a microgrid operator may also need approval from the regional distribution company, which presents a case of conflict of interest, as the latter may view the microgrid as competition.

Microgrids provide a sustainable route out of electricity poverty in the region. Therefore, governments should do all they can to enable their implementation.

[7] See ACT NO. XL OF 1997.

References

[1] "Energy Access outlook, from Poverty to Prosperity," 2017, Available: https://www.iea.org/publications/freepublications/publication/WEO2017SpecialReport_EnergyAccessOutlook.pdf.

[2] N. L. Lam, K. R. Smith, A. Gauthier, and M. N. Bates, "Kerosene: a review of household uses and their hazards in low-and middle-income countries," *Journal of Toxicology and Environmental Health, Part B,* vol. 15, no. 6, pp. 396-432, 2012.

[3] T. K. Baul, D. Datta, and A. Alam, "A comparative study on household level energy consumption and related emissions from renewable (biomass) and non-renewable energy sources in Bangladesh," *Energy Policy,* vol. 114, pp. 598-608, 2018/03/01/ 2018.

[4] J. Thornburg, T. S. Ustun, and B. Krogh, "Smart microgrid operation simulator for management and electrification planning," in *PowerAfrica, 2016 IEEE PES*, 2016, pp. 1-5: IEEE.

[5] K. Ubilla *et al.*, "Smart microgrids as a solution for rural electrification: Ensuring long-term sustainability through cadastre and business models," *IEEE Transactions on Sustainable Energy,* vol. 5, no. 4, pp. 1310-1318, 2014.

[6] A. Jhunjhunwala, A. Lolla, and P. Kaur, "Solar-dc microgrid for Indian homes: A transforming power scenario," *IEEE Electrification Magazine,* vol. 4, no. 2, pp. 10-19, 2016.

[7] K. Shenai, A. Jhunjhunwala, and P. Kaur, "Electrifying India: Using solar dc microgrids," *IEEE Power Electronics Magazine,* vol. 3, no. 4, pp. 42-48, 2016.

[8] P. A. Madduri, J. Poon, J. Rosa, M. Podolsky, E. Brewer, and S. R. Sanders, "Scalable DC Microgrids for Rural Electrification in Emerging Regions," *IEEE Journal of Emerging and Selected Topics in Power Electronics,* vol. PP, no. 99, pp. 1-1, 2016.

[9] D. Gandini and A. T. de Almeida, "Direct current microgrids based on solar power systems and storage optimization, as a tool for cost-effective rural electrification," *Renewable Energy,* vol. 111, pp. 275-283, 2017/10/01/ 2017.

[10] N. Ramchandran, R. Pai, and A. K. S. Parihar, "Feasibility assessment of Anchor-Business-Community model for off-grid rural electrification in India," *Renewable Energy,* vol. 97, pp. 197-209, 2016/11/01/ 2016.

[11] M. Nasir, H. A. Khan, A. Hussain, L. Mateen, and N. A. Zaffar, "Solar PV-Based Scalable DC Microgrid for Rural Electrification in Developing Regions," *IEEE Transactions on Sustainable Energy,* vol. 9, no. 1, pp. 390-399, 2018.

[12] S. Mishra and O. Ray, "Advances in nanogrid technology and its integration into rural electrification in India," in *Power Electronics Conference (IPEC-Hiroshima 2014-ECCE-ASIA), 2014 International*, 2014, pp. 2707-2713: IEEE.

[13] D. Palit and G. K. Sarangi, "Renewable energy based mini-grids for enhancing electricity access: Experiences and lessons from India," in *International Conference and Utility Exhibition on Green Energy for Sustainable Development (ICUE),* \ 19-21 March 2014, pp. 1-8.

[14] D. Palit, G. K. Sarangi, and P. Krithika, "Energising Rural India Using Distributed Generation: The Case of Solar Mini-Grids in Chhattisgarh State, India," in *Mini-Grids for Rural Electrification of Developing Countries*: Springer, 2014, pp. 313-342.

[15] J. Urpelainen, "Energy poverty and perceptions of solar power in marginalized communities: Survey evidence from Uttar Pradesh, India," *Renewable Energy,* vol. 85, pp. 534-539, 2016.

[16] A. K. Srivastava, "Solar minigrids in rural areas of Uttar Pradesh," *Akshay Urja,* vol. 4, no. 6, pp. 16-17, 2013.

[17] P. Loomba, S. Asgotraa, and R. Podmore, "DC solar microgrids — A successful technology for rural sustainable development," in *2016 IEEE PES PowerAfrica*, 2016, pp. 204-208.

[18] C. L. Azimoh, P. Klintenberg, F. Wallin, B. Karlsson, and C. Mbohwa, "Electricity for development: Mini-grid solution for rural electrification in South Africa," *Energy Conversion and Management,* vol. 110, pp. 268-277, 2016.

[19] Z. Xu, M. Nthontho, and S. Chowdhury, "Rural electrification implementation strategies through microgrid approach in South African context," *International Journal of Electrical Power & Energy Systems,* vol. 82, pp. 452-465, 2016.

[20] B. K. Blyden and W.-J. Lee, "Modified microgrid concept for rural electrification in Africa," in *2006 IEEE Power Engineering Society General Meeting*, 2006, p. 5 pp.: IEEE.

[21] J. P. Fossati, A. Galarza, A. Martín-Villate, and L. Fontán, "A method for optimal sizing energy storage systems for microgrids," *Renewable Energy,* vol. 77, pp. 539-549, 2015/05/01/ 2015.

[22] H. A. Khan and S. Pervaiz, "Technological review on solar PV in Pakistan: Scope, practices and recommendations for optimized system design," *Renewable and Sustainable Energy Reviews,* vol. 23, pp. 147-154, 2013.

[23] A. Chaurey and T. C. Kandpal, "A techno-economic comparison of rural electrification based on solar home systems and PV microgrids," *Energy Policy,* vol. 38, no. 6, pp. 3118-3129, 2010/06/01/ 2010.

[24] S. M. Harish, G. M. Morgan, and E. Subrahmanian, "When does unreliable grid supply become unacceptable policy? Costs of power supply and outages in rural India," *Energy Policy,* vol. 68, pp. 158-169, 2014/05/01/ 2014.

[25] D. Debowicz, P. Dorosh, H. S. Haider, and S. Robinson, "A disaggregated and macro-consistent social accounting matrix for Pakistan," *Journal of Economic Structures,* vol. 2, no. 1, p. 4, 2013.

[26] T. Bank, "Agriculture for Development," 2007.

[27] D. Ferris, "Indian micro-grids aim to bring millions out of darkness," *Appropriate Technology,* vol. 41, no. 2, p. 58, 2014.

[28] S. Goel and R. Sharma, "Performance evaluation of stand alone, grid connected and hybrid renewable energy systems for rural application: A comparative review," *Renewable and Sustainable Energy Reviews,* vol. 78, pp. 1378-1389, 2017/10/01/ 2017.

[29] L. Ali and F. Shahnia, "Determination of an economically-suitable and sustainable standalone power system for an off-grid town in Western Australia," *Renewable Energy,* vol. 106, pp. 243-254, 2017/06/01/ 2017.

[30] W. Inam, D. Strawser, K. K. Afridi, R. J. Ram, and D. J. Perreault, "Architecture and system analysis of microgrids with peer-to-peer electricity sharing to create a marketplace which enables energy access," in *Power Electronics and ECCE Asia (ICPE-ECCE Asia), 2015 9th International Conference on*, 2015, pp. 464-469: IEEE.

[31] Q. Bao, T. Honda, S. El Ferik, M. M. Shaukat, and M. C. Yang, "Understanding the role of visual appeal in consumer preference for residential solar panels," *Renewable Energy,* vol. 113, pp. 1569-1579, 2017/12/01/ 2017.

[32] J. Palm, "Household installation of solar panels – Motives and barriers in a 10-year perspective," *Energy Policy,* vol. 113, pp. 1-8, 2018/02/01/ 2018.

[33] S. Matteson and E. Williams, "Residual learning rates in lead-acid batteries: Effects on emerging technologies," *Energy Policy,* vol. 85, pp. 71-79, 2015/10/01/ 2015.

[34] [Online]. Available: http://www.southwire.com/Southwire.htm

[35] K. A. W. Horowitz, R. Fu, T. Silverman, M. Woodhouse, X. Sun, and M. A. Alam, "An Analysis of the Cost and Performance of Photovoltaic Systems as a Function of Module Area,"; National Renewable Energy Lab. (NREL), Golden, CO (United States)NREL/TP-6A20-67006 United States 10.2172/1351153 NREL English, 2017, Available: http://www.osti.gov/scitech/servlets/purl/1351153.

[36] O. Schmidt, A. Hawkes, A. Gambhir, and I. Staffell, "The future cost of electrical energy storage based on experience rates," *Nature Energy,* Analysis vol. 2, p. 17110, 2017.