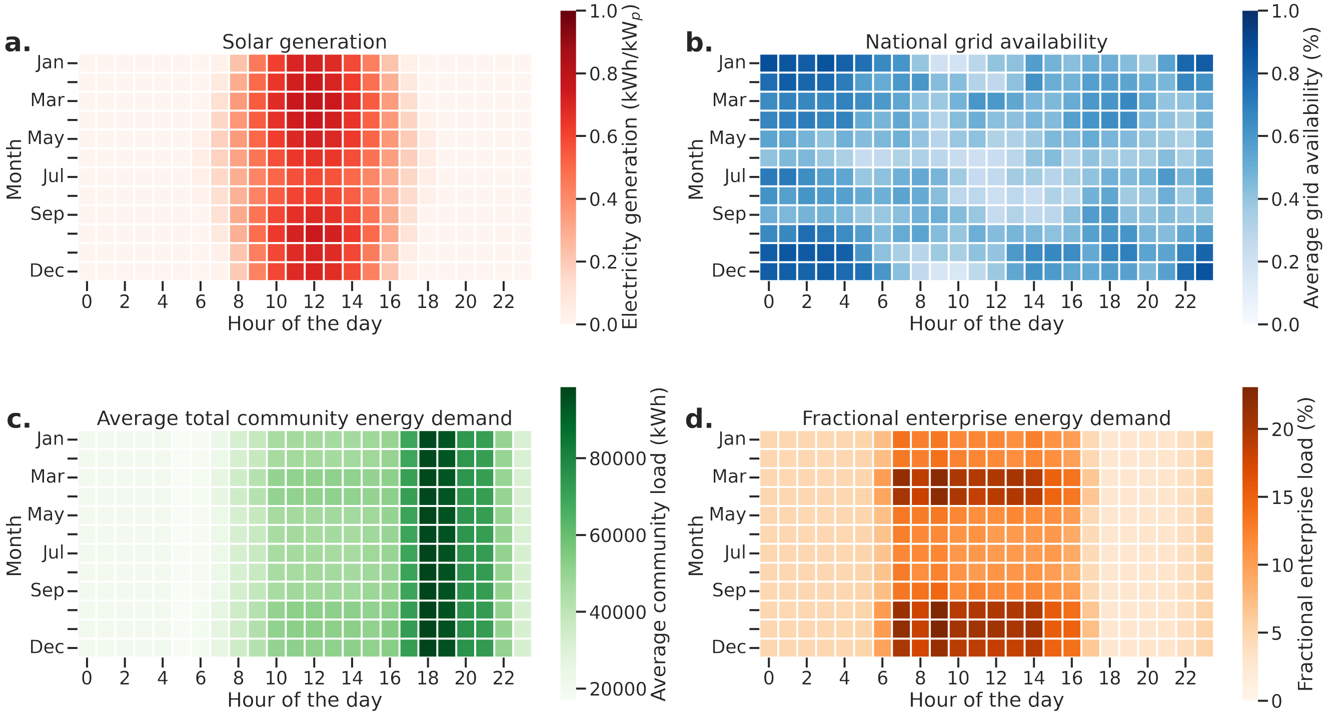
Supplementary Information

Supplementary Note 1: Modelling electricity supply and demand in rural India

The community modelled aims to represent a typical rural community in Uttar Pradesh[1] and comprises 547 households and 66 enterprises. The average solar generation of 1 kW_p of installed PV capacity at the investigation location in Bahraich District, Uttar Pradesh (Supplementary Figure 1a), shows that solar power is typically available from 8:00–17:00 and there is comparatively lower generation, almost halving the hourly output, during the monsoon season between July and September. The relative availability of the grid is generated by modulating the recorded profile for Bahraich District to supply 13 hours per day (Supplementary Figure 1b) based on the average in Uttar Pradesh at the time of data collection being 12.5 hours per day[1]. The grid availability varies significantly both daily (with its lowest availability typically during the daytime) and seasonally (with its lowest availability between March and August).

Supplementary Figure 1c and d show the total load demanded by the community, composed of 547 households and 66 enterprises, and the percentage of the load from the enterprise activities respectively. These are derived from extensive household surveys described in Agrawal et al. (2019)[1] in which those authors describe a representative rural community in Uttar Pradesh and its energy demands. In this work we use these data (Supplementary Figure 1c and d, and Supplementary Table 1), to synthesise demand profiles reflective of daily and seasonal variations. The overall community demand (with an average of 761 kWh/day) is dominated by domestic energy uses (695 kWh/day), with a significant peak between 17:00–22:00 from demand for lighting, entertainment and fans. The commercial demand (66 kWh/day), including agro-processing machinery as well as lighting and appliances in shops, constitutes up to 25% of the total demand at any point in time and is concentrated in March, April, and October to December during the harvesting seasons for rice and wheat when the community milling machine is used the most[2]. The average electricity usage by households (38 kWh/month) and enterprises (30 kWh/month) found by Agrawal et al. (2019) and used here are very similar to those found in other studies[1,3] and correspond to most users having Tier 2 or 3 electricity access under the Multi-Tier Framework[4].



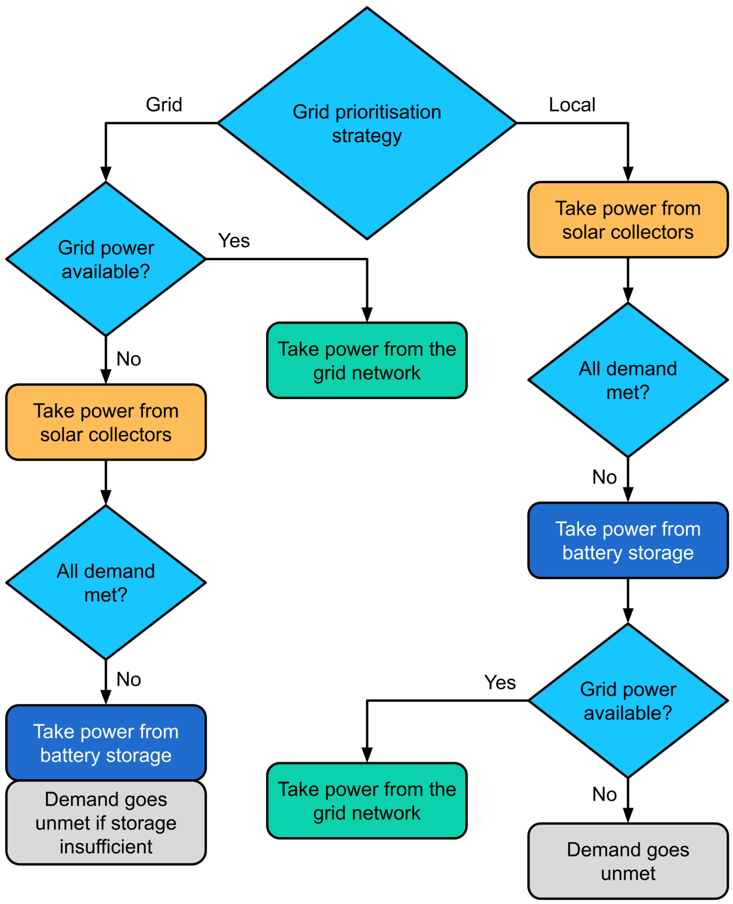
Supplementary Figure 1. Electricity supply and demand inputs to the modelling process: (a) solar generation (kW generation per kW_p), (b) probability of grid availability (shown for the average availability in Uttar Pradesh of 12 hours per day), (c) total community energy demand (761 kWh/day), and (d) proportion of energy demand from rural enterprises.

Supplementary Note 2: CLOVER model operation

Supplementary Figure 2 outlines the process of the model operation within CLOVER for the two scenarios: "grid prioritisation" and "local generation prioritisation." Under the local-generation scenario, the load is considered, the available PV energy is subtracted followed by the available energy from the battery storage. If these are not sufficient, then energy is taken from the grid. Under the grid-prioritisation strategy, energy from the grid is used first to fully meet demand if available. If the grid is unavailable, energy from the PV system is used to meet demand, followed by power from the batteries.

Supplementary Note 3: Grid subsidy schemes

Supplementary Figure 3 shows the percentage difference in the LCUE of systems optimised under an unsubsidised grid tariff of 0.10 \$/kWh compared to those optimised under a subsidised tariff of 0.06 \$/kWh. The colour indicates the fraction of the electricity for the optimised system that was sourced from the grid. The results show an overall increase in the LCUE of the systems, with those systems that rely more heavily on the grid experiencing a greater increase in their LCUE, up to a 4 cents difference (25%) for systems that rely entirely on the grid as a source of power.



Supplementary Figure 2. Flowchart showing the operation of the energy-balance model under both "grid-prioritisation" and "local generation prioritisation" scenarios.

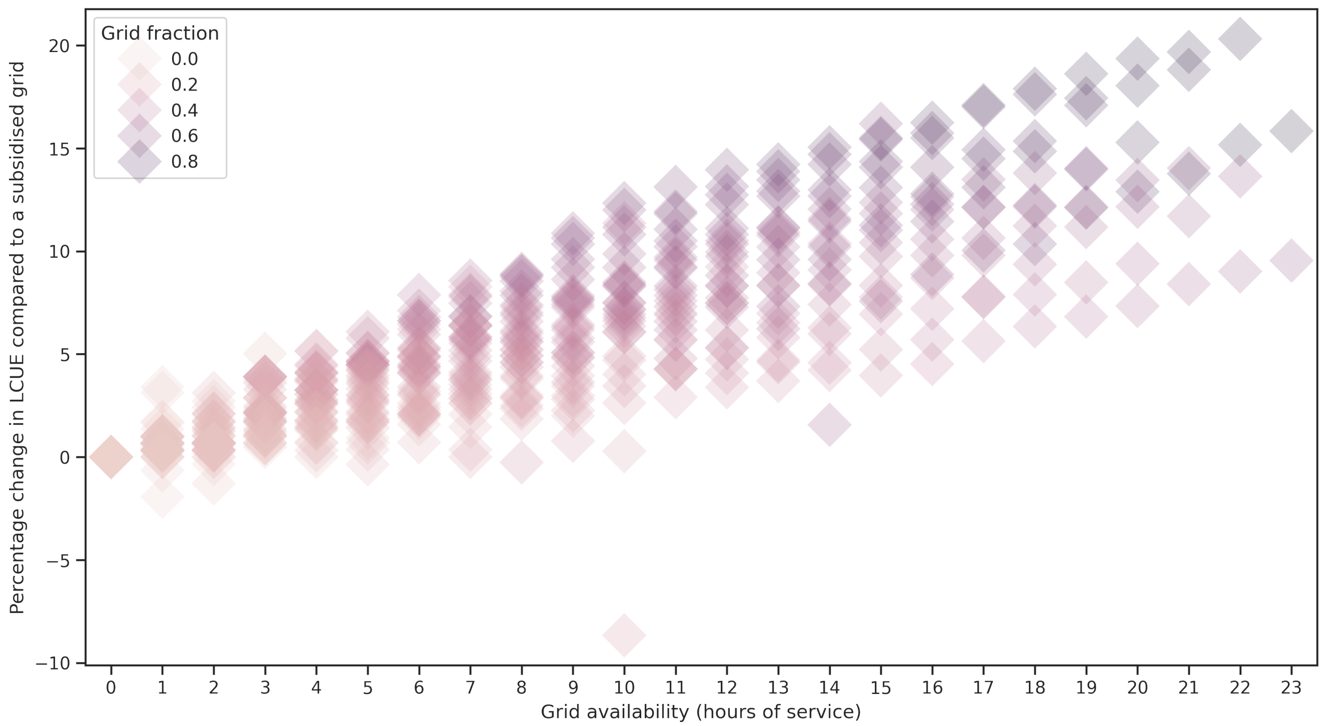
Supplementary Table 1. Ownership, usage and power ratings of a representative rural community in Uttar Pradesh derived from the findings of Agrawal et al. (2019)[1]. The community is composed of 547 households, 66 enterprises and one milling machine for processing crops, the use of which varies seasonally. The power demand and usage of the same appliance type in domestic and commercial settings can vary and is based on the findings of that empirical study.

Demand type	Appliance	Number	Ownership (%)	Usage (hrs/day)	Power (W)
Households (547)	LED bulb	1363	249	4	8
	Incandescent bulb	456	83	3	97
	Phone charger	432	79	3	5
	Table fan	153	28	8	62
	Ceiling fan	291	53	13	72
	Television	190	35	5	36
	Refrigerator	38	7	11	41
	Dessert cooler	31	6	9	224
	Iron	30	6	1	858
	Home water pump	22	4	1	1265
Enterprises (66)	LED bulb	46	69	4	8
	Incandescent bulb	6	1	3	103
	Table fan	18	28	7	72
	Ceiling fan	26	40	8	70
	Refrigerator	9	13	9	41
	Laptop	5	7	6	50
	Printer	3	5	5	350
	Milling machine	1	–	2–7	7460

Supplementary Note 4: Asset stranding

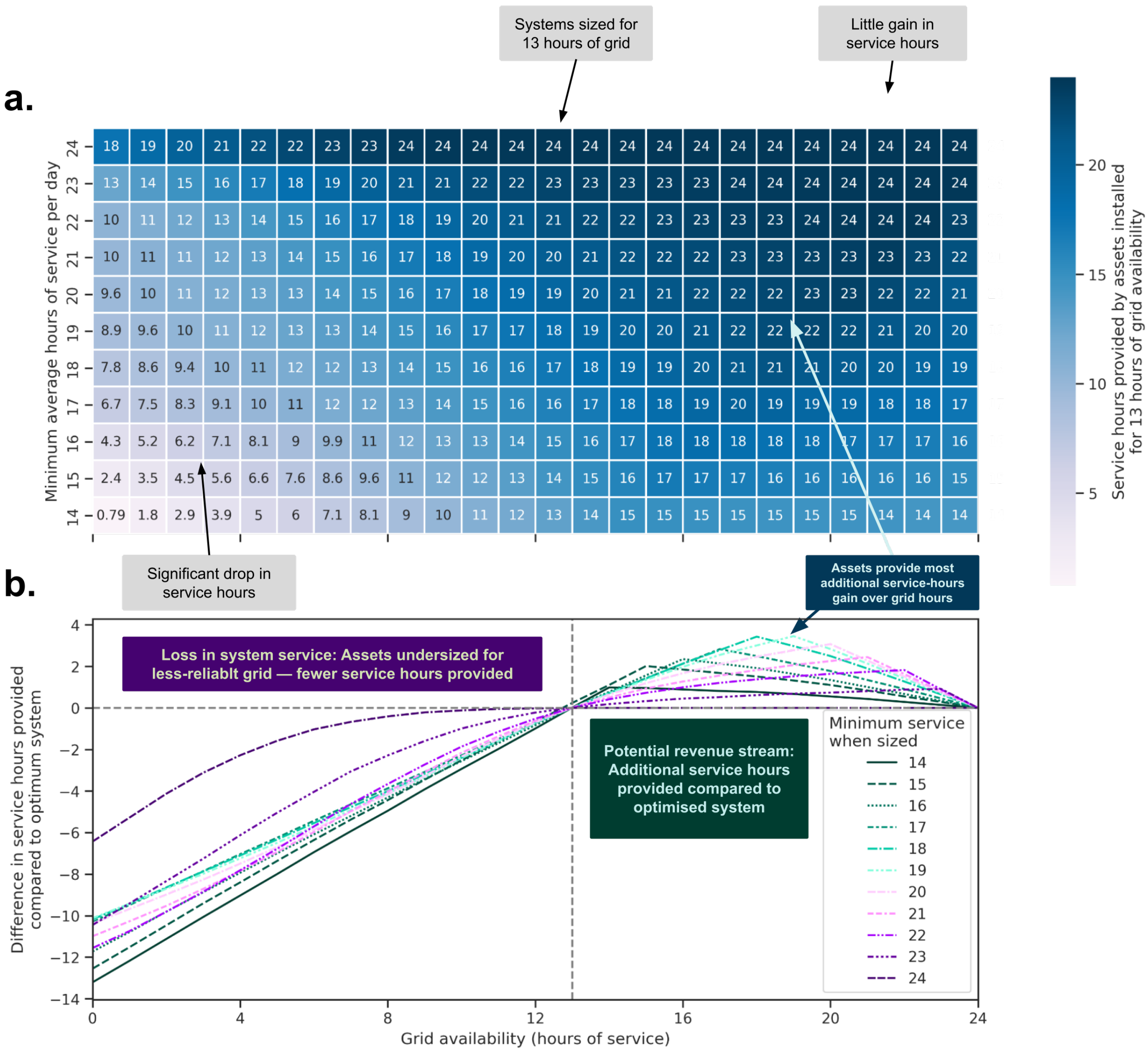
Supplementary Figure 4 shows the total and additional service hours provided for systems that undergo “asset stranding,” whereby the reliability of the grid changes and systems are now either undersized to meet demand (in the event of a reduction in grid service hours) or are stranded and under-utilised (in the event of an increase in grid service hours). Supplementary Figure 4a shows the total number of these service hours as a heatmap, with systems in the centre column (13 hours) operating in the regime of grid electricity that they were optimised under, and those to the left and right operating under a reduced or increased grid service respectively. Visible to the left is a reduction in the total number of service hours provided by these assets as they are no longer correctly sized to meet the electricity requirements of the system. Systems sized for a lower number of service hours are most affected by this, with systems sized for 14 hours of service supplying as little as 0.79, 0.82 and 0.88 hours of service beyond the grid when the grid availability is reduced to 0, 1 and 2 hours of availability. This is due to this system having only a small number of installed assets as only 1 additional hour of service was originally required.

To the right of Supplementary Figure 4a., increases in the grid service hours result in a greater number of hours of service being supplied overall, with assets still able to supply hours beyond those provided by the grid. In Supplementary Figure 4b., the change in the service hours provided is visible. It is clear from the figure that systems sized to meet the largest demand are least affected by the reduction in grid service hours. Less clear, but visible in the figure, is that those systems sized to meet an intermediate number of hours (17–20 hours of service) provide the greatest number of additional hours beyond those provided by the grid, with over 3 hours of additional service provided in the most extreme case. These systems hence provide the greatest



Supplementary Figure 3. The electricity in Uttar Pradesh is currently subsidised for consumers at a rate of 0.06 $/kWh. The effect of changing the rate for grid-sourced electricity to the unsubsidised value of 0.10 $/kWh is shown, with the percentage change in the overall LCUE of the system when removing the subsidy plotted against the average availability of the grid. The colour represents the fraction of electricity that was sourced from the grid for a given system.

resilience against asset stranding as they provide the greatest number of service hours beyond those provided by the national grid which can be utilised and sold to the community as a more reliable service to generate revenue.



Supplementary Figure 4. Service hours provided for systems initially sized to meet a given number of service hours (shown on the y-axis) for 13 hours of grid-electricity availability when the reliability of the grid changes, with increasing reliability shown to the right and decreasing to the left: (a) heatmap, showing the total number of hours for which service was provided, and (b) plot of the difference between the service hours provided by the system sized with 13 hours of grid electricity available and the optimised system as the grid reliability changes. Each line represents a system sized to meet a different number of service hours with 13 hours of grid electricity available.

Supplementary Table 2. Model inputs used for technical specification of mini-grid systems.

Item	Value	Unit	Reference	Notes
Battery depth of Discharge	70	%	5	LFP battery chemistry
Battery leakage	0.004	% per hour	5	LFP battery chemistry
Battery cycle lifetime	2500	Cycles	5	LFP battery chemistry
Battery roundtrip efficiency	86	%	5	
Battery lifetime loss	80	%	6	
Battery c-rate in	0.2		5	
Battery c-rate out	0.2		5	
Transmission efficiency AC	95	%		
DC to AC conversion	95	%		
DC to DC conversion	95	%	7	
Inverter lifetime	10	Years	8	
Solar PV lifetime	20	Years		
Solar PV azimuth	180	degrees		
Solar PV tilt	29	degrees		

Supplementary Table 3. Model inputs used for the economic and GHG assessment of mini-grid systems.

Item	Cost/Value	Unit	Ref	GHGs	Unit	Ref
Solar PV Panels	320	$/kWp	9	790*	kgCO2/kWp	10
Solar PV O&M	1	% of CAPEX p.a	9			
PV Inverter	163	$/kW	11	124*	kgCO2/kWp	12
Battery Storage	250	$/kWh	9	110	kgCO2/kWh	13
Battery O&M	2	% of CAPEX p.a	9			
Balance of System	100	$/kWh	11	134	kgCO2/kWp	12
Discount Rate	8	% per annum	16			
Meter, Connection & Distribution Cost	225	$ per household	5,9			
General O&M	2400	$ p.a.	11			
Grid Tariff	0.06	$ /kWh	14			
Power equipment & integration	256	$ /kW	9			

*Based on manufacture in China.

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