Table 4 | Energy Interventions for Health

NAME OF THE CASE	INSTALLATION TYPE AND SIZE	SERVICES PROVIDED	FOCUS COMMUNITIES	CLIMATE CONTEXT (CURRENT AND FUTURE)	ENERGY CONTEXT BEFORE SOLAR
Boat clinic in Majuli, Assam	3 kW off-grid system on a boat	Run lights, fans, and medical equipment and refrigeration	Serving Mising tribes in *char* areas. One boat clinic serves seven villages during each trip. Focus on women and child health	Island prone to extreme flooding, waterlogging, and rising temperatures	Petrol-based generator for basic needs of the boat clinic Ice pack for vaccine storage
Community Health Centre in Gamharia, Jharkhand	10 kW off-grid system	24/7 electricity for all equipment, lighting, and refrigeration	Health care services for the rural population	The region is prone to thunderstorms, lightning, and high wind speeds. Projected increase in extreme heat days	Unreliable grid connection Diesel generator backup
Nonprofit hospitals in Jharkhand (multiple districts)	7–10 kW off-grid systems in different locations	Patient wards, operation rooms, lab equipment, refrigeration, water supply	Health care for marginalized and poor rural communities	Remote area is prone to thunderstorms and lightning. Increase in the number of extreme heat days	Grid connection with 3- to 12-hour outages Diesel generator backup
Nonprofit health clinic in Rajasthan	1 kW off-grid roof-mounted solar system	Essential lighting and equipment: autoclave, centrifuge, baby warmer, spotlights, fridge, and platform weighing scale	Health care with a focus on tuberculosis (TB) and malnutrition in tribal communities	Projected increase in extreme precipitation events with long dry spells	Single-phase unreliable grid supply
Piped water supply in Sirohi, Rajasthan	3.2 kW off-grid roof-mounted solar system	Piped water supply for 70 households	Tribal communities in remote locations	Hilly terrain in a dry climatic region. The annual average rainfall of 600 mm. Increasing extreme rainfall patterns	Single-phase unreliable grid supply
De-fluoridated water supply in Rajasthan (multiple districts)	1.5 to 2 kW off-grid steel-mounted solar system	De-fluoridated water supply in designated spaces	Communities residing in fluoride-affected areas	Prolonged droughts and water shortages in Jaisalmer. Reduced number of rainy days with extreme rainfall patterns	Single-phase unreliable grid supply

Source: WRI authors.

off-grid solar system helps the clinic offer diagnostic facilities and medical support for ailments such as vector-borne diseases, which are projected to rise in the region with climate change.

Assam's *char* areas are disconnected from the mainland and extremely prone to flooding events, making primary health care or electricity supply challenging to build. A boat clinic is one of the few viable options for ensuring regular health-care access for the 95 *char* villages in Jorhat and nearby districts. A boat clinic requires a decentralized energy source to power medical appliances, vaccine cold storage, and necessary facilities such as lights, fans, and mobile chargers for the staff who stay on the boat. Using solar power instead of a petrol or diesel generator allows the boat clinic to make longer trips and reach remote villages. Refueling is required only to run the boat and not for medical equipment. Solar power also reduces indoor air and noise pollution, runs more medical equipment, and enables refrigeration facilities for vaccines. The clinic is functional year-round and acts as a first response for health care in flood-affected communities, helping prevent post-flood disease outbreaks.

Because electricity is essential for operating health facilities, diesel generator sets have been the electricity solution of first and last resort in the absence of reliable grid connectivity at health centers. Diesel generators are not cost-effective for health facilities, which face challenges in accessing diesel during extreme rainfall, flooding,

and storms. Solar PV installations in these health centers have reduced diesel expenses and allowed for uninterrupted services and better working conditions for staff. They have also allowed access to adequate drinking water, which requires electric pumps.

In Sirohi and Jaisalmer in Rajasthan, groundwater is fluoride-affected, and surface water sources are nonexistent. Groundwater recharge is expected to be reduced due to changing climate patterns, resulting in an increased fluoride concentration in the water supply. Solar-powered water supply and treatment systems improve community health and reduce the burden on women, who take responsibility for fetching potable water. The reduced groundwater recharge can result in resource extraction at further depths, which will increase electricity demand.

Energy Demand for Livelihoods

These case studies cover interventions that improve productivity and income and reduce the risk level in economically backward or marginalized communities that are mostly dependent on agricultural livelihoods. The case studies include regions that are not connected to the grid or that experience unreliable or insufficient single-phase electricity. A summary of the case studies is presented in Table 5.

Solutions such as the floating solar minigrid in Morigaon and the minigrid in Gumla were implemented before the region was grid-connected. They remain relevant because weather events such as floods and thunderstorms disrupt grid electricity. In flood-prone Morigaon, the flood-resilient floating minigrid provides electricity to 21 households. However, it supports only one household's livelihood by powering a fishpond aerator and a solar irrigation pump. In Gumla, the minigrid supports home-based poultry farmers and agribusinesses running cereal and pulse mills, grinders, and mustard oil expellers, as well as non-farm enterprises running vending machines and banking kiosks. These productive loads account for 60 percent of the plant utilization. Gumla is prone to thunderstorms and lightning strikes that cause regular power outages on the grid. Moreover, the single-phase electricity provided to households is insufficient for running small businesses, making a decentralized solution such as solar a crucial enabler for livelihood activities.

Table 5 | Energy Interventions for Livelihoods

NAME OF THE CASE	INSTALLATION TYPE AND SIZE	SERVICES PROVIDED	FOCUS COMMUNITIES	CLIMATE CONTEXT (CURRENT AND FUTURE)	ENERGY CONTEXT BEFORE SOLAR
Floating minigrid in Morigaon, Assam	10 kW off-grid floating solar panels structure on a backyard pond	Electricity provision to 25 households and small enterprises (pond aerator for increasing fish production) in village	Marginalized section of the community that is dependent on small-scale agriculture, fisheries, and livestock for their livelihoods	The village experiences annual flooding and waterlogging from the Brahmaputra river. 70% of the district is flood-prone, with 33% at high risk	Unelectrified
Cold storage in Bongaigaon, Assam	4.5 kW solar PV array system with in-built electricity storage	5 MT cold storage by Ecofrost, which can store seeds and farm produce in temperature ranges between 4 and 10°C	Farmer Producer Organization (FPO) comprises only women farmers	Reduction in annual average rainfall with erratic rainfall patterns, an increasing number of heat days. Also, 24.11% of the district is flood-prone, with 9% being at high risk of flooding	Unreliable grid supply. Due to unreliable grid electricity, cold storages were not viable in that region
Minigrid in Gumla, Jharkhand	35 minigrids of 20–25 kW each	Powers households and village entrepreneurs who have poultry farms, oil expellers, and grain mills	Economically backward communities belonging to the lowest quintiles of the National Family Health Survey (NFHS) wealth index	Thunderstorms with lightning strikes and strong winds and seasonal water shortages, projected increase in the number of days with high temperatures	Unelectrified
Water supply for livestock in Jaisalmer, Rajasthan	Seven installations of 45–60 kW each	Pumps groundwater to ground level reservoirs for human consumption and into troughs for consumption by livestock and wild animals in water-stressed areas	Economically backward, livestock-rearing communities living in extremely remote desert regions	Extreme heat, water shortage, strong winds, and sparse vegetation (desert ecology)	Single-phase electricity connection in the village, hence use of diesel pump sets for pumping water

Source: WRI authors

In Jaisalmer's remote and arid deserts, rearing livestock is the primary livelihood. The region faces severe water shortages, making crop cultivation next to impossible and survival tough for people and their livestock. Although the region is connected to the grid, the electricity supply is unreliable. The remoteness also makes it difficult for any disruptions to be solved on time. Decentralized solar energy systems help in pumping drinking water for use by both communities and their animals.

In Bongaigaon in Assam, members of an all-women Farmer Producer Company (FPC) face erratic and unseasonal rainfall that affects their livelihood by increasing crop and seed rots' risk, among other hazards. With the help of solar-PV-powered cold storage, they can extend the storage time for seeds and other farm produce and reduce losses due to damage and rot. With reliable electricity, farmers can spread their risks by diversifying their livelihoods to include post-harvest processing such as cold storages, milling and grinding, and irrigating fields when rainfall is inadequate.

Electricity plays an essential role in improving the productivity and sustainability of livelihoods dependent on natural resources—agriculture and allied activities—and other market-based enterprises. Solar PV installations, especially in remote and backward areas, allow for productive livelihoods despite challenges that make grid extension unviable.

Planning for Energy Supply: Design Considerations in the Context of Climate Risks

This section discusses how stakeholders in each case planned the implementation of a decentralized solar energy solution and whether climate risks were factored into the projects' technical, operational, and financial design.

Summary of Planning in the Context of Climate Risks

Of our 14 case studies, few installations have factored in the environment and local climate conditions in some form or the other while developing the technical design and operational and financial models. Most of these projects may be responsive to some climatic impacts. They considered recent climatic changes and local knowledge of the environment and weather, such as wind speeds and floodwater levels. Only three installations—the minigrid in Gumla (Jharkhand) and de-fluoridation and remote water supply in Rajasthan—considered current climate patterns from all three aspects: technical, operational, and financial. The minigrid in Gumla added lightning arrestors and surge protectors in response to regular thunderstorm activity. The water supply projects in Rajasthan designed the systems to be resistant to historic high wind speeds. Although the minigrid project in Gumla has started looking at climate projections, none of the other interventions look at future climate risks instead of focusing on historical and current experiences.

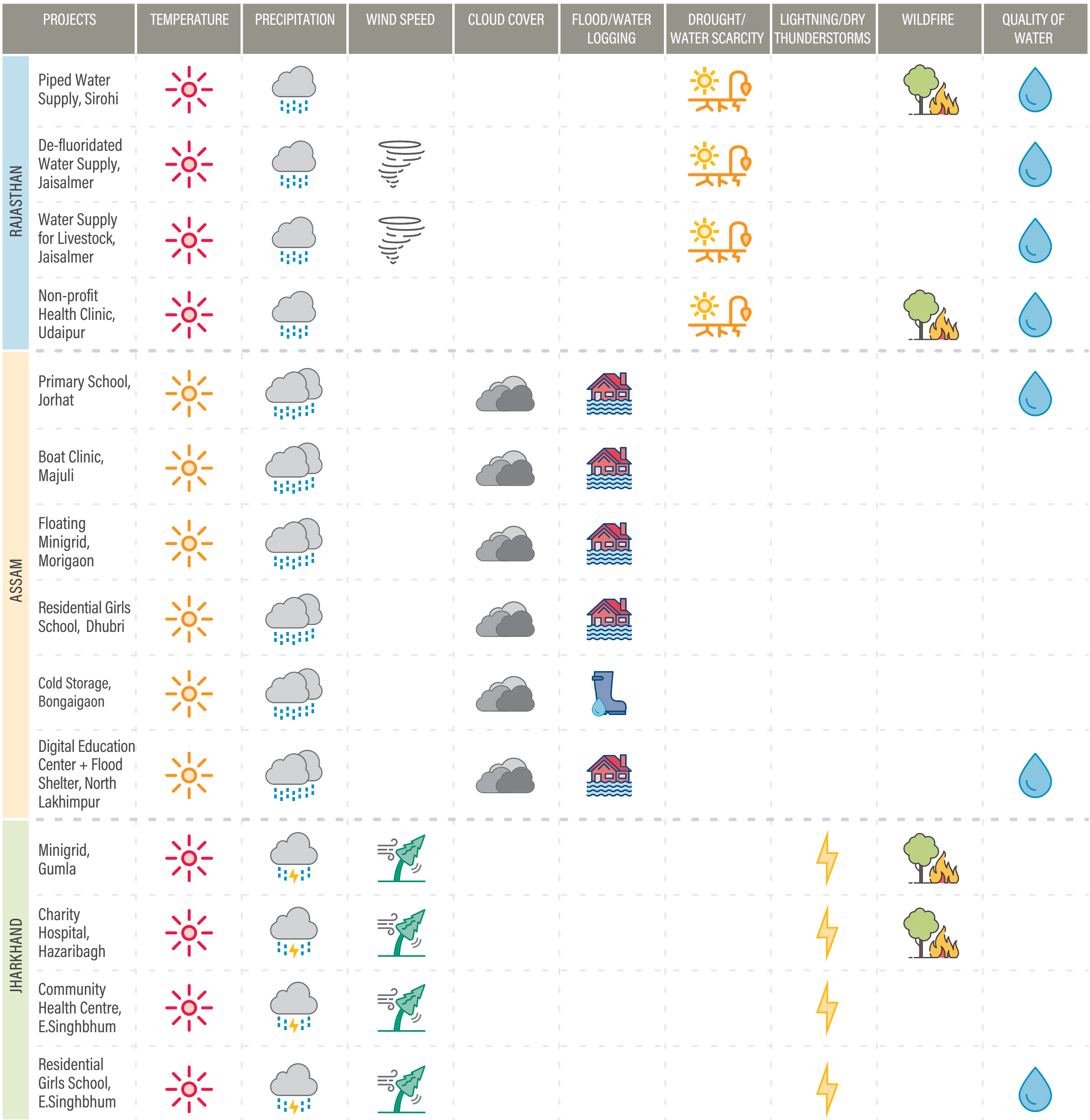
Figure 2 shows the type of climate risks most relevant in each case study as perceived by project beneficiaries and implementers interviewed. The design of the projects considered some of the following current environmental and climate factors. Only one project considered climate projections while designing the project.

Technical Aspects

As the figure shows, different locations in the same state face varied climate risks. In Assam, the significant risk is that of flooding and waterlogging. Some case study installations have designed their systems to mitigate this risk. For example, the floating solar minigrid in Morigaon can function even with a 5 ft water level rise. Here, a ground-mounted solar PV is not ideal as the region is prone to waterlogging, and any available space is needed for crop and fish farming. Most of the houses in this village (as in most parts of Assam) are made of tin and can only support a limited load. A 10.5 KW system would require significant roof space, which is not viable in this case. Given this context, a floating solar solution with adequate battery storage offers a better alternative, as it overcomes the challenges associated with ground/roof-mounted solar. In another case, while selecting the site for the cold storage unit in Bongaigaon, an area not prone to regular floods was chosen, and the solar system was mounted on the roof of the cold storage unit. In North Lakhimpur, the digital education center cum flood shelter is similarly on higher ground and raised further above the current flood levels. The solar panels have been mounted on the roof to reduce the risk further, as is the case with the residential girls' school in Dhubri and Jorhat's primary school. Batteries in all the instances in Assam are stored in raised platforms at heights above current water levels. In addition, Jorhat's primary school has oversized the system to make up for losses during cloudy days.

In Jharkhand, the lightning and temperature variation followed by high wind speeds are the key climate risks that affect the energy installations. The implementing agencies have taken steps to reduce the impact. For example, the minigrid in Gumla has lightning rods, surge protectors, and chemical earthing as precautions against lightning strikes. The minigrid operators keep spare meters in stock to replace the ones affected by lightning strikes at any point in time. They are also actively engaged in research to develop better, innovative solutions to protect their minigrids from lightning damage. In addition to the lightning rods and surge protectors, the community health center in Gamharia and the residential girls schools in multiple locations in Jharkhand are connected to a remote monitoring system to report malfunctions to the implementing agency as well as the energy vendor. These specifications were incorporated at the tendering stage. However, despite precautionary measures, there are also cases of damage being reported, such as in a nonprofit hospital in Hazaribagh. In this case, although there was a lightning arrestor, faulty earthing resulted in damage to the system. Similarly, lightning struck the solar PV installation at one of the residential girls' schools, making it dysfunctional ever since.

Figure 2 | Climate Risks Faced by Each of the Case Study Projects



TEMPERATURE

Region experiences high temperature, increase in number of high temperature days, and length of summer months

Moderate increase in temperature and number of high temperature days

PRECIPITATION

Moderate or no change in rainfall patterns

Increase in extreme precipitation events

Precipitation accompanied by thunderstorms and lightning

FLOOD/WATER LOGGING

Regularly affected by floods and waterlogging

Instances of waterlogging during high rainfall but not prone to floods

WIND SPEED

High wind speeds resulting in sandstorms

High wind speeds that uproot trees

CLOUD COVER

High cloud cover days

DROUGHT/WATER SCARCITY

Regions prone to extreme water scarcity due to droughts, poor recharge capacity, and excess withdrawal

QUALITY OF WATER

Groundwater contamination due to salinity, arsenic, fluoride, or iron

WILDFIRE

Risk of wildfires due to proximity to forest areas

LIGHTNING/DRY THUNDERSTORMS

Increased risk of lightning strikes owing to increased dry thunderstorms and monsoon storms

Note: All the regions must factor in cloud cover, but the ones highlighted in the tables are regions with dense cloud cover for a higher number of days.

Source: WRI authors.

In Rajasthan, extreme heat can reduce the efficiency of solar panels and batteries. The solar projects for the health facilities and water supply and purification systems have been installed with 30 percent excess capacity to allow optimum output due to efficiency loss and cloud cover on rainy days. The water supply projects by the Public Health Engineering Department (PHED) in Rajasthan have been designed based on human and livestock population growth for seven years, as reflected in the tank capacity. Because Jaisalmer faces sandstorms and high wind speeds, the solar de-fluoridation unit's steel structure is designed to weather high wind speeds of up to 200 kmph and a wide range of temperatures. The unit structure is a 20 ft mild steel (MS) frame structure on a concrete base. The other challenge in states such as Rajasthan is water shortage. All installations in Jaisalmer are planned as interim measures for a fixed term of seven years, assuming that groundwater withdrawal will no longer be sustainable due to geological and climatic conditions. At the end of seven years, these projects are expected to be decommissioned and replaced with more sustainable options available at the time.

Although climate risks have been considered while designing the systems, factoring of risk is conspicuously absent post installation. For example, in water-stressed areas, the project's sustainability depends on the sustainability of the water source. In such cases, when groundwater recharge is currently not part of the design, as in the case of installations in Rajasthan, it can affect the performance of the system in the future.

Operational Aspects

In several of our case studies, the implementing agency is an energy expert; for example, the state nodal agencies for renewable energy such as Assam Energy Development Agency (AEDA), the Jharkhand Renewable Energy Development Agency (JREDA), and energy enterprises such as Mlinda in Jharkhand.

None of the nonprofit implementing agencies have a sole focus on energy as part of their operations. These agencies include the Seven Sisters Development Assistance (SeSTA), Indo-Global Social Service Society (IGSSS), Innovative Change Collaborative (ICCo) & Reaching and Educating At-risk Children (REACH) India, Centre for North East Studies and Policy Research (C-NES), Basic Healthcare, and Centre for Micro Finance (CmF). Of these, IGSSS and C-NES worked closely with a partner with energy expertise (SELCO Foundation) through all the implementation stages. The remaining implementing agencies relied on internal technical expertise or vendors' expertise in the open market for implementing their solutions (see Figure 1 for a summary of the agencies and the interventions they implemented).

Where implementing agencies are energy experts, precautions were taken to incorporate climate risks in the technical design, but this did not necessarily ensure operational clarity in terms of roles and responsibilities. Operational clarity enhances coordination among multiple stakeholders, which is essential for building climate resilience. For example, in the case of a residential girls school in Jharkhand, when the solar system broke down, the school administrators were not clear regarding whether it was their responsibility or JREDA's to arrange for repair and pay for it. In the case of the floating solar minigrid in Morigaon, installed by AEDA, community members declined to use or pay for electricity from the minigrid once grid electrification reached the village. Interventions that integrate design considerations while also clarifying roles and responsibilities and ensuring local buy-in are functional and better equipped to respond to developmental needs and climatic impacts.

Decentralized solar energy installations have the flexibility of being installed, maintained, and operated by either centralized agencies such as state-level nodal agencies or decentralized models of community management. JREDA, Catholic Health Association of India (CHAI), PHED, and C-NES projects provide examples of centralized ownership structures. In JREDA schools and hospitals, the vendor contracts directly with JREDA and not with the individual schools or hospitals. The same is the case with CHAI hospitals. As a result, even though the schools and hospitals are encouraged to contact the vendor directly to resolve problems, the vendor is not obliged to respond, causing delays and service disruptions. This is particularly important when weather events directly damage the systems (e.g., lightning strikes in Jharkhand). In the case of PHED and C-NES, although the contracts are centralized, the facility-level operations are co-managed with the energy vendor, which reduces the burden of coordinating between different agencies for ongoing operations and maintenance (O&M). At the residential girls school in Dhubri, the primary school in Jorhat, and the nonprofit health clinic in Udaipur, the energy installations are owned and managed at the facility level. In such cases, stakeholders involved do not have the capacities or bargaining power to ensure that the project meets local needs, has adequate maintenance provisions, or incorporates climate considerations beyond what is offered by the solar vendor.

Community members play critical roles in 5 of the 14 case studies. The solar installations to supply piped water in Sirohi and the floating solar installation in Morigaon are owned and managed by a village committee. In these cases, the energy vendors agree with the village representatives to provide maintenance services, usually for a fixed term funded by user fees. Beyond that term, it becomes the village committee's responsibility to ensure that the energy system remains functional and in use. The village committee also sets up mechanisms to collect user fees from energy consumers to pay for ongoing maintenance. In Bongaigaon's cold storage, the FPC owns and is primarily responsible for the solar installation. The minigrid in Gumla is run by a social enterprise that follows a slightly different approach. It draws up a service agreement with the village representatives, under which it selects the site for minigrids and pays rent for the lease of land where the solar panel arrays and operating house with battery backup are set up. The minigrid installation includes transmission and distribution wires for villages and meters for each user who pays for the electricity. Community engagement in these case studies has made implementing agencies and vendors more accountable and empowered the community to make decisions regarding their energy needs. This equips them to respond better to climate-related events.

Many of the case study installations have locally hired or trained operators. These operators may or may not work for the energy vendor. The minigrid in Gumla and the remote water supply and de-fluoridation projects in Jaisalmer and Sirohi recruit and train local operators to handle operations and conduct preventive maintenance as part of the energy services provision. With this, lead times reduce significantly for responding to operational challenges and disruptions that arise from unexpected weather events. In the remaining installations, local operators are usually residents or staff of the facility where the energy system is installed. In these installations, although the operators may know how to maintain the system functions on an ongoing basis, they receive little to no training on extensive