troubleshooting. They are dependent on the vendor for diagnostics and resolution of every issue. In the case of the cold storage in Bongaigaon, this is partially resolved by proactive remote monitoring by the energy vendor.

Financing Aspects

The financing models for the interventions studied were either grant-based or publicly funded, which sometimes included user fees. Three of the installations (the floating solar minigrid in Morigaon, a primary school in Jorhat, and piped water supply in Sirohi) used a community's financial or workforce contribution during installation. Stakeholders in these interventions feel that such payments from the community are instrumental in garnering long-term commitment from the beneficiaries by creating a sense of ownership and interest in ensuring the system's upkeep. In addition, accountable arrangements to track contributions and utilization of funds are also essential to building trust in the implementation agency.

Financing for maintenance of installations varies among the case studies. The O&M costs of three projects (the floating solar minigrid in Morigaon, a primary school in Jorhat, and piped water supply in Sirohi) are funded entirely or partially by the beneficiaries' contributions. The minigrid in Gumla covers its O&M costs from its service charges. Three other projects (the boat clinic in Jorhat, flood shelter cum digital resource center in N. Lakhimpur, and nonprofit hospitals in Jharkhand) included fixed five-year O&M contracts in their installation grants. By contrast, four other projects (de-fluoridation in Sirohi, water supply for livestock in Jaisalmer and community health center in Gamharia, and the residential girls schools in Jharkhand) have fixed-tenure O&M contracts serviced by public sources of funding. The remaining four projects studied did not have O&M arrangements and had to meet these costs by themselves. Even when funds were kept aside for O&M contracts, they were often nominal, as with the floating solar minigrid in

Morigaon. Morigaon did not have funds to replace batteries at the end of their three- to five-year lifespan. Large-scale interventions, such as those involving nonprofit and government hospitals in Jharkhand, leave O&M to be covered by the facility budgets, which can be onerous, especially when damaged parts need replacement.

An interesting model deployed by PHED in Rajasthan utilized a staggered payment schedule that released 65 percent of the total contract amount to the vendor as initial capital and allocated the remaining 35 percent to O&M. The latter was released in annual installments over seven years. This model does not require annual maintenance contracts, which are typical of other projects. In addition, the agreement designed by the PHED includes a sunset clause, stipulating an end to the project period. After seven years, when the O&M tenure expires, the contract is either extended by the PHED, or the vendor is asked to remove the installations and return the use of the allocated space to the PHED. Although the average life of solar installations is more than seven years, this arrangement gives the PHED the option of exploring other electricity sources after the contract expires. Furthermore, because the installation's practical ownership remains with the vendor throughout the contract, there is an implicit commitment from the vendor to maintain and ensure the security of the structures. Note that such arrangements could potentially exclude small-scale energy enterprises from participating in such contracts because of the higher costs.

Even though these interventions are in climate vulnerable areas, many did not consider insurance for losses due to wind, lightning, or flood damage, or cover supply delays caused by loss of road connectivity. Only a few case study installations considered insurance, specifically those with water pumping as the primary intervention because pump insurance already exists as a market product. Because there are no specific products for solar PV insurance, our installations also did not procure such coverage. However, some of them did face challenges and risks that insurance could cover. Overall, only five installations allocated a separate budget for regular upkeep from the beginning. Four of these five installations allocated money for the potential damage caused by extreme weather events.

The case studies have demonstrated that climate-related events impact electricity provision in grid-connected areas and that RE interventions have proved beneficial in reducing the cost of electricity access, improving the service provision at schools and health centers, and increasing the short-term productivity and long-term sustainability of livelihoods. On delving further, we see that there are considerations related to sizing, siting, and designing the installations that are important to ensure the sustainability of the structure in the face of climate change. During the life of the installation, clarity on roles and responsibilities, capacity development of the stakeholders involved, and community engagement are essential for the smooth operation of the installations. Financial arrangements to cover the costs of operations, maintenance, and troubleshooting either in the form of budget outlays, O&M contracts, and user fees are essential for sustaining the installations. There is scope for innovative business models with various partnership models, as has been demonstrated by some case studies.

CHAPTER 4

IMPLICATIONS FOR DECENTRALIZED SOLAR SOLUTIONS IN CLIMATE VULNERABLE REGIONS

Ensuring the sustainability of energy systems is an area of concern for decentralized solar energy practitioners. Decentralized solar energy systems are expected to have a long usable lifetime, but often fail to meet expectations because of technical, financial, operational, and logistical problems.

Ensuring the Sustainability of Installations

A recent report, *Lasting Impact: Sustainable Off-Grid Solar Delivery Models to Power Health and Education* (UN Foundation and SEforAll 2019), explores this issue in depth for health and education facilities in South Asia and sub-Saharan Africa. The report identifies critical insights to be kept in mind by stakeholders wishing to undertake off-grid solar projects for community facilities. The insights relate to projects' technical, organizational, and economic aspects and span four stages of project life cycles: inception, design, build, and O&M. We borrow this framework to support additional considerations that stakeholders need to keep in mind while working in climate vulnerable areas, based on our observations from the case studies.

Technical Considerations

Technical considerations include the interactions between the electricity infrastructure and the environment in which it operates, as shown in Table 6. They include the current and future climate risks in the region, how they affect the demand for and supply of electricity, and what technology options, codes, and guidelines exist to ensure that the energy system remains useful and functional. It also looks at whether climate risks are included in project timelines during implementation and whether the technical design considers the market availability of spare parts in the event of any disruptions.

Different climate-related events can affect decentralized solar-powered systems differently depending on the type of event and its intensity. We have not identified any comprehensive guidelines on how decentralized solar systems should be designed to mitigate the risk of different climate events. However, we summarize some standard practices noted from the case studies and recommendations on resilient infrastructure from the literature in Table 7. This table discusses the potential impacts of climate-related events on decentralized solar installations and the technical design considerations for mitigating the risks. Box 1 discusses ongoing mapping initiatives on climate and energy by WRI that can support design considerations.

Table 6 | Technical Considerations at Various Stages in a Project

INCEPTION AND DESIGN PHASE	▪ What climate risks does the location currently face? ▪ What climate risks will the location face during the lifetime of the energy project? ▪ How is the energy demand affected by climate risks? Is this effect factored into the design of the energy system? ▪ How will various climate risks, individually or combined, affect the energy infrastructure? ▪ What electrical, structural, and product design standards should the project follow to factor in the climate risks? ▪ Are there technology options to proactively monitor and respond to climate risks?
IMPLEMENTATION PHASE	▪ Are all the required electrical, civil, and product design codes being followed? ▪ Have the climate risks been factored into the project life cycle?
O&M PHASE	▪ Are there local markets for components that are specifically affected by or required to respond to climate risks? Is there a need to procure and stock essential spare parts? ▪ Are the operational guidelines for taking care of the energy system during extreme weather events specified?

Note: O&M = operations & maintenance.

Source: WRI analysis, based on recommendations for resilient infrastructure by Williamson et al. (2009), OECD (2018), Hallegatte et al. (2019), and UN Foundation and SE4All (2019).

Table 7 | Impact of Climate Change on Off-Grid Solar Infrastructure

CLIMATE CHANGE, UNCERTAINTIES, AND HAZARDS	DIRECT POTENTIAL IMPACT ON INFRASTRUCTURE	DESIGN CONSIDERATIONS TO MITIGATE RISK
Temperature	Increased temperature can reduce solar cell efficiency Extremely high temperature can reduce the carrying capacity of lines depending on the transmission distance Extreme heat and cold can affect battery life and efficiency	Include efficiency loss in energy demand calculations Where possible, use components that can withstand high temperatures Improve air circulation below and in between the panels Factor in replacement costs for components and batteries whose life can be affected by extreme temperatures
Precipitation	Increased precipitation days can reduce productivity Increased precipitation intensity can damage parts of the system Heavy downpour and persistent rainfall can damage the distribution lines	Limit exposure of wiring and distribution cables to rainfall
Wind speed	High/cyclonic wind speeds can damage the infrastructure Winds can damage distribution lines by affecting connecting points	Follow structural design codes to design wind-resilient structures
Cloud cover	Reduced array output due to reduction in insolation	Include efficiency loss in energy demand calculations
Lightning	Direct strikes can damage parts of the system and transmission lines	Add lightning and electrical surge arrestors at source and the consumer level
Flood/waterlogging	Can damage the system and transmission lines	Elevate the system above ground based on historical flooding/waterlogging, soil data, and flooding projections
Drought	Reduced availability of water can result in dust accumulation, leading to reduced efficiency of panels If the water supply is dependent on solar energy, the problem is exacerbated, and the usability of the energy system is compromised	Design dust removers that are not dependent on water in drought-prone regions Use recycled water
Wildfire	Increased dry periods can lead to wildfires that can damage the infrastructure	Choose fire-resistant modules
Landslides	Precipitation-induced (or earthquake-induced) landslides can damage the infrastructure	Assess local topographical and geological conditions for selecting an appropriate site and follow structural design codes to avoid damage
Quality of water	Turbidity and salinity can result in scouring of the panels pH levels and other contaminants such as iron in water can have a corrosive effect on mounting structures and foundation	If dust removal is via washing, add water filter/softener as required and where feasible Follow structural design codes for foundations in contaminated water table regions Use anti-corrosive modules and structure
Indirect impacts—Increased precipitation, high wind speeds, and flooding can affect the response time of the maintenance crew and availability of parts		

Source: WRI analysis, based on recommendations for resilient infrastructure by Williamson et al. (2009), OECD (2018), and Hallegatte et al. (2019).

Box 1 | Using Geospatial Information for Location-Specific Decision-Making

Climate change is a global challenge, but adaptation planning occurs at various levels: local, regional, national, and international. "Planned adaptation to climate change means using information about the present and future climate change to review the suitability of current and planned practices, policies, and infrastructure" (Fussel 2007). In addition, adaptation planning requires human development and environmental indicators to assess the current situation and project future requirements.

Location-specific planning for development and adaptation needs can be supported by geospatial analytics, which can help planners understand existing local conditions, trends, and probable future climatic events using multiple indicators. The Partnership for Resilience and Preparedness (PREP) and the Energy Access Explorer (EAE) are examples of geospatial data analytics for planners to support decision-making.

Climate Information Services are used widely. One of the significant benefits of converting climate data to spatial visualization is that it enables users to analyze and add value to data (Giuliani et al. 2017) and supports informed decision-making. PREPdata (www.prepdata.org) is a free, open-source data platform that provides accessible, curated data that decision-makers need to analyze vulnerability and build climate resilience. It allows users to easily access highly credible climate, physical, and socioeconomic datasets from multiple sources, including the National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, United States Geological Survey, European Space Agency, and Indian Institute of Tropical Meteorology. Users can visualize a specific region's vulnerability; track the indicators most relevant to their work on customizable dashboards; request that data providers add new tools or datasets to PREPdata; and share their analyses with adaptation practitioners worldwide. The platform's wide-ranging datasets include extreme weather events, precipitation, drought and flood risks, social vulnerability, coastal energy facilities, landslides, sea level rise, global urban heat island effect, reservoirs and dams, global cropland extent, and more. Details on the accuracy, granularity, and source of each dataset are available on the website.

GIS-based modeling helps decision-makers develop electrification policies, identify technologies, and design location-specific cost-effective electricity supply systems for diverse users (Mentis et al. 2016). WRI India's EAE (https://www.energyaccessexplorer.org/) is an interactive online platform that compiles and analyzes several spatial datasets across the development and electricity sectors. It is a significant effort that helps visualize energy access gaps, focusing on unmet and undermet electricity needs for social and institutional facilities such as hospitals and schools. These maps will provide both a state of play and establish benchmarks for future decision-making in the sector.

Organizational Considerations

Organizational considerations for factoring in climate risks related to the roles, responsibilities, and expectations of all the stakeholders involved in or affected by the energy project are shown in Table 8. Considerations include whether the contractual and non-contractual responsibilities of all the participating organizations are laid out if a climate-related event were to occur, and whether they have adequate capacity and flexible internal mechanisms to execute their roles and responsibilities. An essential component of organizational aspects is a careful examination of the community's expectations and how they will be affected by the energy project, including energy's role in their current and future coping mechanisms to address climate risks.

Economic Considerations

Economic considerations for energy projects in climate vulnerable areas relate to the financial resources available to plan for, implement, and maintain a climate resilient system. As discussed in Table 9, they involve a realistic estimation of whether the funding plan regards climate resilience as a key priority and has addressed the integration of financing options to hedge against the uncertainty caused by climate risks in the short and long term.

Our analysis of the case studies suggests that although energy projects largely consider the technical aspects of planning for climate resilient systems, they often fall short when planning for economic and organizational sustainability in the face of climate risks. Although currently there are no customized insurance products for challenges