Climate Risk and Resilience Toolkit for Minigrids in Rural Africa

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CONTENTS

List of Acronyms

ADFD	Abu Dhabi Fund for Development
AfDB	African Development Bank
AMP	Africa Minigrids Program
CARE	Cooperative for Assistance and Relief Everywhere
ESIA	Environmental and Social Impact Assessment
FAO	Food and Agriculture Organization
GEAPP	Global Energy Alliance for the People and Planet
GEF	Global Environment Facility
GHG	Greenhouse gases
Ha	Hectare
IMG	Interconnected Minigrid
IPCC	Intergovernmental Panel on Climate Change
M&E	Monitoring and Evaluation
O&M	Operations and Maintenance
PMU	Project Management Unit
PUE	Productive Use of Energy
PV	Photovoltaic
RE	Renewable Energy
RMI	Rocky Mountain Institute
SES	Social and Environmental Standards
UNDP	United Nations Development Programme
USAID	United States Agency for International Development
WMO	World Meteorological Organization

EXECUTIVE SUMMARY

Rural African communities face severe challenges from climate change, including increasingly frequent floods, droughts, storms, and shifting rainfall patterns. These impacts disrupt livelihoods, damage essential infrastructure, and strain already limited access to services such as healthcare, education, and energy.

Minigrids have emerged as a critical solution for expanding electricity access in these communities. Their distributed, renewable energy-based systems can provide reliable, affordable power where national grids are absent or unreliable, while supporting local economic activities. Yet, like the communities they serve, minigrids are exposed to climate risks, from extreme weather events damaging infrastructure to gradual shifts affecting system performance and financial sustainability. Although climate resilience is gaining traction across the energy sector, its momentum in the minigrid space has not kept up with the rate at which climate change is impacting rural African communities.

For minigrids to fulfil their potential as a resilient, sustainable energy solution, climate risks must be integrated into project planning, design, and operations. This goes beyond technical considerations: minigrid sustainability is closely linked to the resilience of the communities they power. Minigrids must provide affordable, reliable electricity even during climate shocks, maintaining functionality and service quality as conditions evolve.

This toolkit provides a practical framework to help AMP's Project Management Units, minigrid developers, planners, and policymakers systematically integrate climate risk and resilience considerations into all phases of minigrid project development and operations. It offers clear guidance on:

- Assessing climate risks and vulnerabilities.
- Identifying and prioritizing resilience measures.
- Embedding resilience into procurement, design, and operations.
- Monitoring and adapting resilience strategies over time.

Additionally, the toolkit highlights four complementary actions to strengthen community resilience alongside minigrid resilience:

1. Building the capacity of local institutions and leaders.
2. Establishing community-based disaster response teams.
3. Adopting climate-smart agricultural practices.
4. Promoting sustainable water resource management.

While focused on rural African contexts, the framework is adaptable to other regions and project types facing similar climate challenges.

INTRODUCING THE AFRICA MINIGRIDS PROGRAM (AMP)

Overview of the AMP

The Africa Minigrids Program (AMP) is a country-led regional technical assistance programme for minigrids, active in an initial 21 African countries. It is led by the United Nations Development Programme (UNDP) with funding from the Global Environment Facility (GEF) and implemented together with Rocky Mountain Institute (RMI) and the African Development Bank (AfDB).

AMP's objective is to expand electricity access by improving the financial viability of renewable energy minigrids and attracting scaled-up commercial investment. The programme focuses on reducing costs across hardware, software, and financing, as well as fostering innovative business models. By lowering costs, minigrids become more financially sustainable, commercial capital flows increase, and end-users benefit from lower tariffs and expanded service.

The programme operates through two pillars:

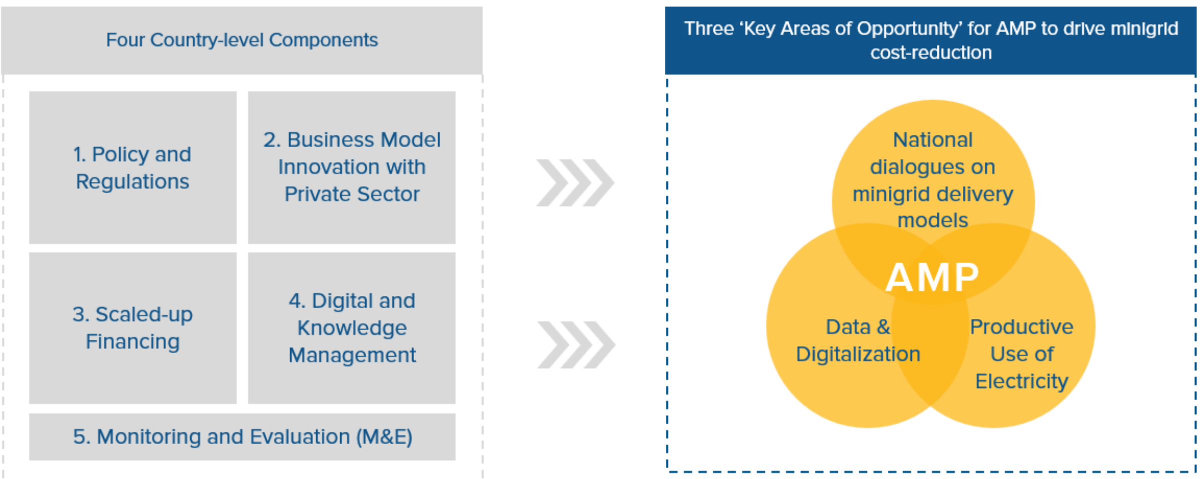
- 21 national projects[i], each focusing on: (i) policy and regulations, (ii) private-sector business model innovation, (iii) innovative financing, (iv) data and digital tools, and (v) monitoring and evaluation (M&E).
- A regional platform offering knowledge tools, technical assistance, operational support, and promoting digital solutions to reduce minigrid costs.

AMP's strategy centres on three key areas of opportunity:

1. Advancing national dialogues on minigrid delivery models.
2. Promoting productive uses of electricity.
3. Leveraging data and digital solutions for cost reduction.

This dual approach - country-level implementation backed by regional support - positions AMP as a distinctive actor in Africa's minigrid ecosystem.

Exhibit 1: AMP key areas of opportunity



Eswatini, Madagascar, Malawi, Nigeria, Somalia, and Sudan; Cohort 2 — Benin, Chad, Mali, Mauritania, Niger, Sao Tome and Principe, and Zambia; Cohort 3 — Burundi, DRC, and Liberia.

AMP's second area of opportunity — promoting productive uses of electricity — directly connects to the second component of national projects: business model innovation involving the private sector. Under this component, each national project supports investments in up to three types of minigrid pilots designed to demonstrate cost-reduction opportunities. See Table 1 for full descriptions.

Table 1: Types of minigrid pilots in AMP

Type of pilot	Description
Greenfield minigrids	Minigrid systems usually built in previously unconnected areas; they include generation and distribution assets, and in some cases, productive use equipment. In some instances, minigrids can be interconnected to larger grids to expand the electricity supply and/or help stabilize the grid system, therefore reducing technical and commercial losses.
Hybridization of diesel-based mini-grids	Retrofitting (i.e., hybridization) of existing fossil-fuel-based minigrids to increase the renewable fraction of power generation and reduce the operations and maintenance costs.
A productive use overlay to an existing or planned minigrid	Investments in productive use appliances and equipment — and if needed in minigrid system enhancements — to increase the number and energy consumption of productive users of power connected to an existing or planned minigrid, this can help generate additional income, improve users' ability to pay for services, and improve utilization of minigrid assets.

To help scale sustainable minigrid policies and practices, AMP established the Africa Minigrids Program Community of Practice (AMP-CoP), a peer-to-peer working group aimed at fostering collaboration and knowledge exchange. The AMP-CoP brings together representatives from African governments, rural electrification agencies, the private sector, academia, and international organizations to jointly address challenges in minigrid development.

Through this platform, practitioners and experts share lessons and coordinate efforts to accelerate sector growth. The AMP-CoP focuses on advancing effective policies, creating enabling regulatory frameworks, promoting viable business models, and unlocking financing to attract private investment, all contributing to the broader objectives of AMP.

Scope and objectives of the Climate Risk and Resilience toolkit

This toolkit is a practical guide to mainstreaming climate change adaptation strategies into minigrid project development. The toolkit offers valuable insights into building climate-resilient minigrids and leveraging minigrids to improve the resilience of rural communities.

After reading this toolkit, the reader will:

- Be equipped with knowledge of climate change impacts on minigrids and rural communities
- Be able to identify climate hazards and develop a climate hazard exposure matrix to understand past, current, and future climate change impacts;
- Understand the underlying causes of vulnerability and rate climate risks;
- Identify resilience measures for incorporation in minigrid project design and implementation; and
- Monitor and reassess the outcome of measures implemented.

This toolkit has been developed for AMP's Project Management Units, minigrid planners, energy sector decision makers, civil society, and social groups concerned with practical approaches for increasing minigrid resilience to climate change. Ultimately, minigrid developers and planners need to assess the cost implications of the risk and resilience measures outlined in this toolkit to ensure that the combination of measures selected is cost-effective. The increased costs from resilience measures are often offset by the long-term benefits of the minigrid's electricity services.

Sections in the toolkit

The remaining sections of this toolkit are organized as follows:

- Section 1 outlines climate change impacts on rural communities in Africa.
- Section 2 discusses the role of minigrids in increasing resilience in communities with relevant case studies.
- Section 3 outlines how the viability of minigrids can be affected by both the direct and indirect impacts of climate change.
- Section 4 defines a resiliency framework and identifies resilience measures that can be integrated into minigrids across the project life cycle to build resilient minigrids.
- Section 5 discusses four key measures minigrid developers and communities can use to collaborate to improve the community's resilience to climate change.[ii]

[ii] A "minigrid developer" as used in the toolkit refers to a sector actor who designs, builds, and operates a minigrid. Depending on the minigrid delivery model, they can either be a private developer, a utility, or a government agency.

Integrating Climate Risk and Resilience into Minigrid Projects

The design, execution, and monitoring of climate risk and resilience in minigrid projects follow a three-phase approach, with each phase encompassing several steps. The three phases outlined in this toolkit are depicted in Exhibit 2.

Exhibit 2: Phases of integrating climate risks and resilience into minigrids

	Phase	Outcome
Phase 1	Minigrid Project Planning	Minigrid vulnerability and risk matrices
Phase 2	Project Procurement and Execution	Shortlist of priority resilience measures
Phase 3	Monitoring and Evaluation	Monitor and re-assess the resilience measures guided by an O&M and emergency response strategy

Phase 1: Project planning — Understanding exposure to climate hazards, and assessing and ranking vulnerability and risk

Understanding exposure to climate hazards involves identifying specific direct environmental threats, such as floods, storms, and extreme temperatures, that a minigrid may encounter, as well as indirect threats the minigrid may be exposed to, including impact on demand patterns. Assessing vulnerability requires analyzing the susceptibility of the minigrid infrastructure and its components to these hazards, considering factors including location, design, and maintenance practices. Ranking vulnerability and risk involves prioritizing these threats based on their potential impact and likelihood, and allowing operators to focus on the most critical areas. This comprehensive approach ensures that mitigation strategies are effectively targeted, enhancing the resilience and reliability of minigrid in the face of climate change.

Phase 2: Procurement and execution — Identifying and prioritizing resilience measures and integrating resilience into minigrids

Identifying and prioritizing resilience measures for minigrids during the procurement and execution phase involves evaluating potential adaptations such as flood defenses, wind-resistant structures, and enhanced cooling systems for batteries to address identified climate risks.[iii] This process includes a cost-benefit analysis to determine which measures provide the most significant protection for the least investment, ensuring efficient allocation of resources. Integrating resilience into minigrid design and operation entails incorporating these prioritized measures into the planning, construction, and maintenance phases. By

[iii] Project execution includes all activities related to installation and commissioning of the minigrid.

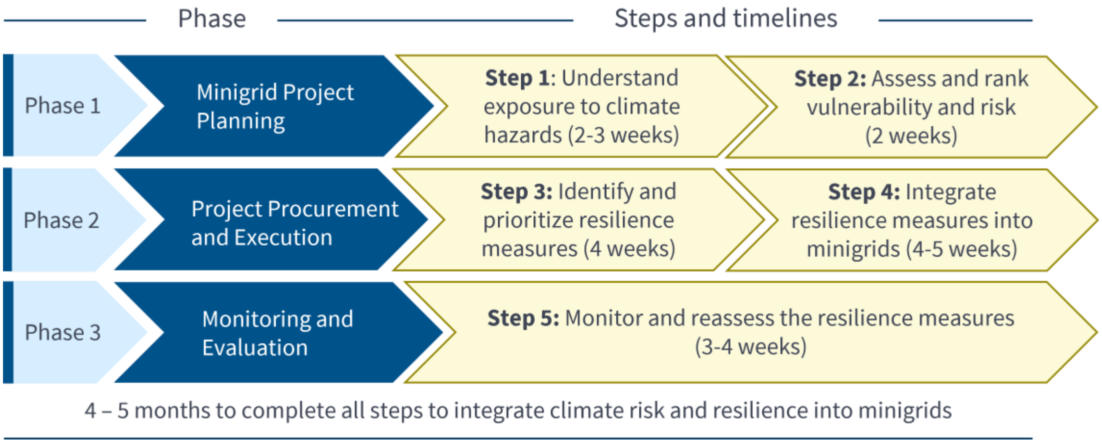
embedding resilience into every phase of the minigrid life cycle, minigrid developers can enhance system durability, reduce downtime, and ensure continuous energy supply despite adverse climate impacts.

Phase 3: Monitoring and Evaluation — Monitor and reassess the resilience measures

Monitoring and evaluating the resilience strategy for minigrids involves regularly collecting and analyzing data on system performance and climate impacts. This includes regular data collection and analysis to detect any deviations or failures in the system. Doing so provides insights and lessons that guide the development of early warning systems to protect minigrids and the communities they serve. It is critical to address environmental, technical, commercial, and social concerns as they arise and adapt to ensure the sustained performance of the minigrid. Periodic assessment should be conducted to review and update the resilience strategy, incorporating new data and insights from recent climate events. Engaging with local communities and stakeholders is crucial to gather feedback and adapt the strategy to evolving conditions, ensuring sustained resilience and reliability of the minigrid system.

The steps and considerations provided in this guide are designed to be relevant to all rural African communities. However, it is important to note that this guide may not encompass all country-specific considerations for integrating climate risks and resilience into minigrids. Therefore, users should incorporate local specificities and nuances when integrating climate risks and resilience into minigrids. The following summary table introduces the phases and steps explained in detail later in this document.

Exhibit 3: Timeline to integrate climate risk and resilience into minigrids



1. CLIMATE CHANGE AND ITS IMPACTS ON RURAL AFRICAN COMMUNITIES

1.1. Most rural African communities are susceptible to climate change impacts

Africa is the least climate-resilient region in the world, with high climate change vulnerability and low response capacity.[1] More than 690 million people live in rural African communities, where households derive about two-thirds of their income from agricultural activities.[iv,2] This reliance on rain-fed agriculture and informal livelihoods makes them particularly sensitive to climate risks.

According to the Intergovernmental Panel on Climate Change (IPCC), rural communities feel the impacts of climate change the most, particularly through disruptions to water supply, food security, and agricultural income.[3] The Food and Agriculture Organization (FAO) estimates that poor rural households in Africa experience significant income losses each year, with heat stress reducing their earnings by about 5% and floods by 4.4%.[4] These losses are especially severe because most rural community members live on less than US$2 a day and rely heavily on agriculture for their livelihoods. It is estimated that about 95% of African agriculture depends on rainfall. By contrast, only 6% of arable land in Africa is irrigated, compared to 14% in Latin America and 37% in Asia.[5] This makes African farmers very vulnerable to weather fluctuations. Given

[iv] This rate is higher than the average in other developing countries.

this overwhelming reliance on rainfall, even small changes in weather patterns can severely disrupt crop production and lead to lower household income levels.

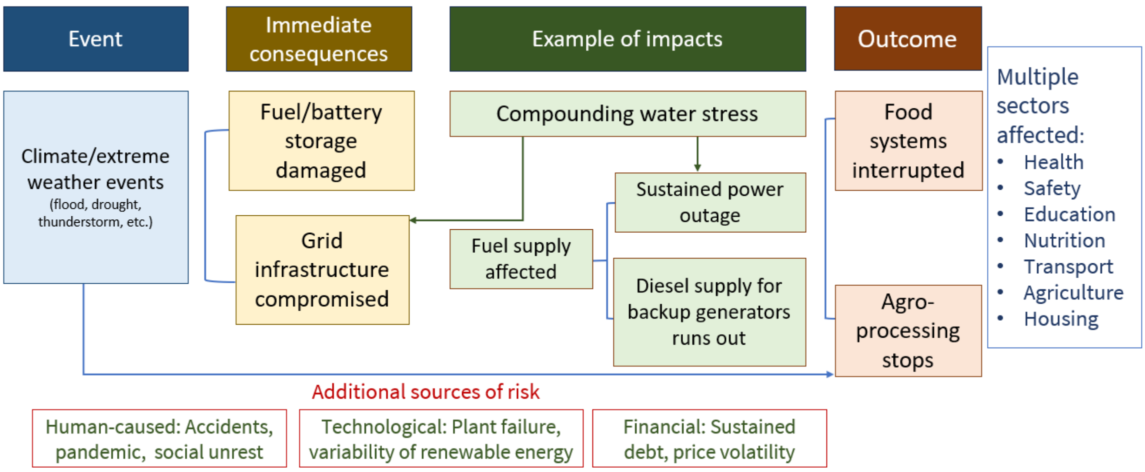
Delays in rain arrival, early cessations, and extreme weather events such as floods and storms can lead to subpar harvests or even complete crop failure. For instance, climate change is projected to reduce cereal output potential in Africa by 16% to 27% by 2080, with some countries facing declines of up to 60%.[6] These long-term risks stem from rising temperatures, erratic rainfall, and water scarcity, highlighting the scale of the challenge. Similarly, a marginal rise in local temperatures can result in reduced productivity for communities in lower latitudes, especially in seasonally dry and tropical regions. This unpredictability also disrupts agricultural planning, impacting crucial activities like processing.

As rural African economies depend heavily on agriculture, these disruptions pose a serious threat to livelihoods. For example, over 80% of businesses in a rural town in South Africa lost over 50% of their employees and revenue due to drought.[7] If repeated across multiple regions, such localized economic shocks could significantly undermine broader development efforts.

However, challenges extend beyond agriculture. Extreme weather events such as floods and windstorms damage essential infrastructure in rural areas, including homes, roads, productive appliances, and electric equipment. Heavy rains and subsequent flooding can wash away unpaved roads and bridges, isolating communities, disrupting transportation and trade routes, and damaging electricity-generating equipment, such as solar panels. This directly impacts essential services such as education and healthcare, compounding hardships. In addition, extreme heat can strain power grids and reduce the efficiency of power generation. According to the IPCC's sixth Assessment Report, in 2019, cyclones Idai and Kenneth flooded districts in Mozambique, Zimbabwe, and Malawi with huge loss and damage to infrastructure in the energy, transport, water supply, health, and education sectors.[8] These repeated shocks highlight the scale of the resilience gap rural communities face.

Changes in precipitation patterns can lead to prolonged droughts or floods, both of which can affect the availability and quality of water. Droughts reduce water availability for drinking, irrigation, and sanitation, while floods contaminate water sources, thus exposing rural households to certain diseases such as malaria, typhoid, and cholera. Coastal and rural communities are particularly susceptible to flooding. For example, Mozambique (2019,[9] 2020, 2024[10]), Nigeria[11], Malawi[12], Ethiopia[13], and Senegal[14] have experienced recurrent severe floods over the past five years, causing sustained welfare losses. Exhibit 4 illustrates the impacts of climate change on different sectors of rural African communities, placing continuous pressure on local resilience systems and community well-being.

Exhibit 4: Impact of climate change on rural African communities. (Source: RMI)



The increased incidence of diseases like malaria, typhoid, and cholera leads to a decrease in workforce productivity, impacting income generation and making families more susceptible to shocks. Combined with agricultural losses and infrastructure damage, these health risks contribute to a broader pattern of poverty and vulnerability across rural African communities.

Table 2: Potential impacts of climate change on communities

Climate change	Impact on communities
High Temperatures	• Reduced crop yields, especially for heat-sensitive crops, leading to reduced income • Increased prevalence of pests and diseases • Increased evaporation leading to reduced water availability for irrigation • Limited availability of clean water for drinking, cooking, and washing • Death of livestock and reduced plant yield
Flooding and sea level rise	• Increased crop loss from damage caused by flooding • Increased soil erosion leading to reduced agricultural productivity • Prevalence of diseases such as malaria and cholera • Damages to houses and flooding of shops, making personal belongings and equipment unusable
Storms, hurricanes, typhoons	• Severe damage to community infrastructure such as schools, roads, and hospitals, thereby limiting the availability of public goods • Destruction to homes and livelihoods

Furthermore, climate change makes certain areas less habitable due to extreme weather, water scarcity, and reduced agricultural productivity, leading to the migration of rural communities. This migration gradually weakens both the social and economic fabric of these communities. Persistent flooding and prolonged droughts, coupled with their detrimental effects on rural farming livelihoods, are forcing the productive labor force to seek opportunities elsewhere. For instance, rural populations living in coastal areas in Bangladesh migrate to nearby urban centers like Dhaka due to frequent flooding.[15]

This population outflow leads to a decline in electricity demand, making it difficult for minigrid operators to sustain their services due to reduced revenue. Consequently, minigrids may face operational challenges, including difficulties in covering maintenance costs. At the same time, the departure of skilled labor hampers local economic growth and productivity, exacerbating the overall vulnerability of rural communities. Maintaining minigrid financial sustainability is therefore intrinsically linked to the broader resilience and economic stability of the community. In this context, minigrids are both a resilience solution and a system dependent on community stability for long-term viability. This situation is compounded by the decline in agricultural productivity caused by climate change, as farmers lose their primary income source and are compelled to migrate in search of alternative livelihoods.

Climate change is severely eroding community resilience across Africa by intensifying and increasing the frequency of extreme weather events. These events trigger a cascade of challenges, including health crises, disrupted livelihoods, and damaged infrastructure. While communities may recover from individual shocks, repeated crises strain coping mechanisms beyond their limits. As a result, communities are overwhelmed, struggling to recover and rebuild. Moreover, shifting rainfall patterns and rising temperatures disrupt traditional livelihoods and agricultural practices, further destabilizing communities and increasing vulnerability to poverty and food insecurity. Faced with these compounding challenges, communities are finding it increasingly difficult to maintain stability.

2. MINIGRIDS CAN CONSIDERABLY INCREASE COMMUNITY RESILIENCE

In rural African communities where the grid is mostly unreliable or not present at all, minigrids are increasingly being adopted as a low-emissions alternative to improve energy resilience against climate change impacts[v].

Minigrids improve energy supply reliability and security in rural communities, given their distributed nature. Their modular design enables quicker deployment of clean electricity to rural communities, particularly where grid expansion may not reach in the near term. This makes minigrids a unique solution for providing a faster response to climate change hazards. Additionally, in most rural remote geographies, often more cost-effective than traditional grid expansion. Specifically, solar minigrids offer a lower greenhouse gas emissions alternative compared with expensive, polluting fossil-fueled generators. The World Bank estimates that minigrids could offer the least-cost solution for 380 million people in sub-Saharan Africa, with cost declines forecasted to reach $0.20/kWh by 2030.[16] This would ultimately reduce rural communities' dependency on fossil fuel, reducing CO_2 emissions and climate impact.

By providing energy access that powers economic activities such as agro-processing or shops (e.g., tailoring, welding), minigrids also have the potential to increase income from improved agricultural productivity and service activities. In communities without existing non-agricultural economic activities, the increased access to electricity gives rise to new service activities such as phone charging stations, enabling the community to diversify income sources. The increased revenue and diversified income sources support communities in sustaining climate shocks affecting their agricultural activities.

Agro-processing, such as milling grain into flour or pressing oil from seeds, adds value to crops and increases marketability. Electricity access through minigrids reduces the need for farmers to travel long distances to access processing services, thereby cutting transport costs and minimizing post-harvest losses. Cold storage solutions powered by minigrids further enhance agricultural productivity. Perishable goods such as fruits, fish, dairy, and vegetables can be stored under optimal conditions, extending their shelf life and reducing post-harvest losses, which tend to increase as temperature levels rise over time. This capability allows for strategic sales, enabling farmers to sell their products when market prices are higher, boosting their incomes.

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[v] Section 2 provides details on how minigrids can improve community resilience.

With increased access to electricity, minigrids also strengthen essential services such as healthcare, education, and communication systems, key pillars of community resilience that are otherwise vulnerable to climate-related disruptions.

Mali case study – Minigrid for irrigation

Like most rural African communities, farmers in Bougoula, a rural community in south-western Mali, travel long distances to fetch water to irrigate their farms. With funding from IRENA/Abu Dhabi Fund for Development (ADFD) Project Facility, a hybrid solar minigrid was installed in Bougoula to provide electricity and to power water pumps, agricultural processing machines, and other industrial equipment. Electricity supply from the minigrid is used to irrigate about 50 hectares of fields, benefitting approximately 600 farmers.

Source: IRENA, 2022[17]

Nigeria case study – Minigrid for cold storage

In Kiguna, a rural fishing community in Nigeria, local fishers and traders struggled to keep their fish fresh. The majority of their fish harvest either went bad or was sold at a loss to consumers. The only preservation method was through smoking over burning wood. To address this, a solar minigrid was installed to power a 3-ton cold storage facility at a temperature of -30 degrees Celsius. The Coldbox Store, as it is popularly called, can hold up to 3,000 kg of fish every week. This enables fishers and traders to store and sell their fish at profitable prices rather than losing up to 50% of their catch to spoilage, as happens to most Nigerian fishermen. For a typical fisherman, this translates to about US$350 more in profits every year. It also reduces the community’s exposure to fine particulate and carbon monoxide. This has significantly improved livelihoods at Kiguna.

Source: RMI, 2023

Improved energy security and reliability

The distributed nature of minigrids allows for wider geographic diversification of energy sources, unlike centralized conventional power plants. This reduces the possibility of a single, significant loss of power from a climate hazard, increasing power system resilience, particularly in grid-connected communities.

Additionally, minigrids, when combined with efficient energy storage technologies, can provide back-up power during grid outages or disasters. Increasingly, minigrids are being designed with black-start capabilities using grid-forming inverters to increase their ability to recover from a system collapse.[vi] Minigrids interconnected with the main grid can operate in island mode during outages, ensuring power supply to consumers even when the grid is down. Minigrids that can isolate from the main grid ensure that consumers still have electricity even when the main grid is down and can also be reconfigured to power critical loads such as healthcare facilities during a power outage. During Kenya's longest blackout in August 2023, which lasted for close to 24 hours, the 13.5 kW Kitonyoni solar PV minigrid continued to power the community, school, and hospital.[18]

Faster response to climate change hazards

The modular nature of minigrids makes it possible to increase the generation of electricity at a faster pace than large-scale systems to respond to increased electricity demand. This offers an opportunity for minigrids to be used to support critical loads in the event of short-term climate-related disasters. Additionally, given that minigrids are located close to load centres and are modular, they can address issues at specific locations of the grid and respond more quickly to changes in load profiles from climate-related events such as cloud cover. Where minigrids are connected to the main grid, it is critical to develop robust interconnection plans to ensure effective integration with the existing grid. The case study below shows how a minigrid can provide a fast response to climate change hazards.

India case study – Tara Urja minigrid supplied power amid severe flooding

In late August 2017, Bihar, a remote state in India, faced severe flooding that disrupted life for millions and overwhelmed local authorities. Amid uncertainty over grid power, renewable energy minigrids, like the one operated by Tara Urja, an NGO in Nabiganj district, became crucial. These minigrids provided reliable electricity, particularly to the Block Development Office, a government-owned building that coordinated flood relief efforts.

When rising waters threatened villages and the office's power supply, Tara Urja quickly established a dedicated power line overnight and ensured continuous electricity. This reliable power was vital for coordinating relief work in the affected areas. Tara Urja's response highlights the effectiveness of decentralized renewable energy systems in swiftly responding to climate change hazards.

Source: Power for All, 2017[19]

[vi] Black-start refers to the ability of a power generation facility (e.g., a minigrid system) to restart parts of the power system to recover from a blackout. Grid-forming inverters are an emerging technology that allows inverter-based energy sources such as solar to independently restart the grid.

Reduced dependency on fossil fuel

The integration of renewable energy minigrids reduces the consumption and dependency on fossil fuels, decreasing greenhouse gas emissions and reducing future adaptation needs.[vii] In Mlinda, a rural community in India, solar minigrids reduced fossil fuel consumption by 50%, resulting in a 75% savings on fossil fuel expenditure.[20] The reduced dependence on fossil fuel can also mitigate health hazards from pollution.

Increased income and improved agricultural productivity

Minigrids are revolutionizing rural communities by improving productivity through the electrification of value chain activities such as irrigation, threshing, drying, milling, and incubation. By unlocking a range of previously untapped or undervalued activities, minigrids enhance agricultural output, leading to increased income, welfare gains, and economic resilience for farmers. Beyond farming, minigrids power service activities such as welding and barber shops, diversifying local economies. Income from such service activities supports revenue diversification of rural economies and sustains a community's resilience when climate change impacts agricultural productivity.

One key benefit of minigrids is their ability to support irrigation systems. By providing a steady power supply for electric irrigation pumps, minigrids enable year-round cultivation and the expansion of arable land. Allowing farmers to grow multiple crops throughout the year enhances resource-use efficiency and contributes significantly to food security, especially in geographies experiencing climate-induced changes to precipitation patterns. In Malawi, a solar minigrid is improving the lives of 600 farmers by powering irrigation systems for 50 hectares of farmland through the Bakasala Irrigation Scheme.[21] In Ethiopia, where only 5% of the country's arable land is irrigated, the Distributed Renewable Energy (DRE) – Agriculture Modalities programs seek to build nine large-scale irrigation systems powered by solar minigrids.[22]

Improved access to information and communication

Minigrids can significantly expand communities' access to information, such as live news on climate events and trends. They provide an avenue to collect data that can help build resilience and disseminate information on early warning signs. For instance, before the implementation of a minigrid at Kudorkope, an island in southern Ghana, only two televisions were present on the island, and people had to travel to charge their phones to access information. After the minigrid's commissioning, however, several of the inhabitants now own televisions and electric radio sets, allowing them to access life-saving information.[23]

[vii] According to IPCC, adaptation need refers to circumstance requiring action to ensure safety of populations and security of assets in response to climate impacts.

3. CLIMATE CHANGE THREATENS THE VIABILITY OF MINIGRIDS

Although minigrids offer a compelling solution for climate resilience in rural communities in Africa, they are also vulnerable to the same climate change impacts that affect rural communities and national grid electricity services. Minigrids are vulnerable to near-term extreme events that can pose a threat to property, infrastructure, and agricultural production, and long-term impacts such as through air temperatures and precipitation. These risks can reduce the efficiency and performance of minigrids and directly damage the minigrid system. This section presents the direct and indirect impacts of climate change on minigrids.

1. **Direct impacts on minigrid components**

Adverse climate change impacts, including heat, thunderstorms, flooding, and windstorms, have pronounced effects on minigrid infrastructure.

Heat: Excessive temperatures can significantly impact minigrid performance. Studies have shown that for every degree rise in temperature, the efficiency of a solar panel decreases by 0.3%–0.5%.[24] This can greatly reduce the electricity generated by as much as 25% if the solar panel becomes very hot.[25] Heat also degrades battery performance and lifespan,[26] increasing maintenance costs and replacement needs. Additionally, thermal stress on electrical components, such as batteries and inverters, can cause overheating and increased resistance,[27] resulting in energy losses and potential equipment failures. The combined effects translate to lower energy output, more frequent maintenance, and potential instability of the distribution network.

Thunderstorms: Thunderstorms can damage critical equipment such as inverters and smart meters, disrupting billing and customer trust. In a rural community in Nigeria, a thunderstorm damaged smart meters, leading to free electricity consumption for customers for two months due to the inability to replace them on time. This resulted in strained relationships when customers were later billed for the accumulated usage.

Flooding: Flooding can inundate and damage electrical components such as solar panels and battery storage systems. This leads to outages, costly repairs, and extended downtime. In Tanzania, for instance, it is estimated that businesses lose US$101 million annually due to power outages caused by rain and floods.[28]

Windstorms: High winds can cause power lines to become entangled or disconnected and can damage poles or solar panels. Windstorms can also accelerate the accumulation of dust and debris on solar panels, significantly reducing power generation. In January 2022, Tropical Storm Ana disrupted the power supply in large parts of Malawi after damaging a power plant. Similarly, Storm Batsirai, which hit Mauritius in February 2022,[29] knocked down trees onto electricity lines, leaving at least 7,500 homes without power.

Table 3: Potential impacts of climate change on minigrids

Climate change	Impact on minigrid
High Temperatures, heat	• Reduced efficiency and capacity • Reduced distribution capacity • Increased demand for cooling and irrigation
Flooding and sea level rise	• Damage to low-lying power infrastructure, such as distribution transformers • Increased saltwater and equipment corrosion • Reduced generation efficiency and capacity • Erosion and scouring of system foundations and components
Storms, windstorms, hurricanes, typhoons	• Damage to power and distribution components from debris, wind, and lightning • Reduced minigrid lifespan • Power disruptions

2. **Indirect impacts on minigrid operations**

Disrupted load patterns: Climate change can affect agricultural and industrial processes that rely on minigrid power. This can alter energy consumption patterns, making grid management more challenging. For example, extreme weather events might disrupt agricultural production, leading to fluctuations in electricity demand for customers using productive-use appliances or equipment.

Increased payment defaults: Financial hardship caused by climate events can make it difficult for users to pay electricity bills, straining the minigrid's financial health. For instance, prolonged periods of drought can severely reduce agricultural yields, leading to reduced income for farming households. A recent study estimates that climate change can reduce crop earnings in Africa by 30%.[30] This kind of economic strain can result in higher rates of payment defaults, as residents prioritize essential needs such as food and water over utility bills. In turn, reduced cash flow can limit the minigrid operator's ability to maintain and expand services, ultimately threatening the long-term sustainability of the energy supply.

4. BUILDING CLIMATE-RESILIENT MINIGRIDS

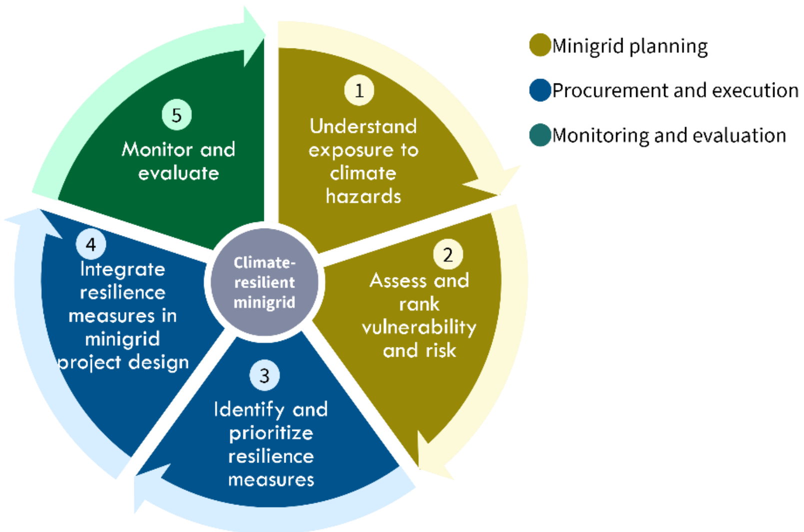
Minigrids' ability to successfully drive economic development in rural communities is contingent on their response to climate change impacts and the community's capacity to sustainably pay for electricity. Minigrid planners must anticipate climate risk and integrate resilience considerations into the process of designing, constructing, and operating minigrids. Failure to incorporate climate change considerations in the planning and design of minigrids can lead to significant revenue loss and increased consumer expenditure for energy. Incorporating climate risk adaptation strategies in developing minigrids increases the resilience of rural communities to climate change impacts.

4.1 Defining a resilience framework

A framework is needed to guide the implementation of minigrids in a way that integrates climate considerations and improves the capacity of minigrids to be more resilient to climate hazards. The framework proposed in this toolkit aims to achieve this through a five-step process to utilize tools that effectively identify, anticipate, and adapt minigrids to climate hazards. The framework consists of action-oriented recommendations that must be undertaken at different phases of the project development life cycle. This is particularly necessary for decision-making purposes because climate risks can occur at different points in time over a project's life. For each action item, we identify a set of stakeholders to clarify roles and responsibilities. While the minigrid operator is responsible for all actions, it is important to engage other stakeholders, including community leaders and local government authorities. Table 4 presents a matrix showing stakeholders that must be responsible, accountable, consulted, and informed.

The resilience framework aligns with the three phases of a minigrid's development life cycle: project planning, procurement and execution, and monitoring and evaluation. The framework applies across these three phases as shown below.

Exhibit 5: Resilience framework for minigrid



This framework seeks to guide Project Management Units (PMUs) and other project teams to understand and effectively prepare for the risks posed by climate change through a resilience approach. It is also intended to help identify project development functions that need to be strengthened to build up climate-resilient minigrids and support the implementation of a combination of prioritized resilience measures across the project life cycle.

Minigrid project development activities under each of the three phases can vary widely across different projects. Action-oriented recommendations for each phase of the development of climate considerations are given in Table *4*.

Table 4: RACI Matrix

Project phase	Action	Responsible	Accountable	Consulted	Informed
Minigrid project planning	1. Understand exposure of the community to climate hazards by evaluating past, current, and future risks; identify underlying causes of vulnerability to climate change; and evaluate the impact of potential vulnerabilities	Minigrid developer	Project sponsors and financiers	Community leaders Local government agencies	Minigrid end-users
	2. Assess and rank vulnerability and risk, as well as climate linkages to livelihoods	Minigrid developer	Project sponsors and financiers	Community leaders	Minigrid end-users
Project procurement and execution	3. Identify and prioritize resilience measures	Minigrid developer	Project sponsors and financiers	Local government agencies	Minigrid end-users Local government agencies
	4. Integrate resilience measures in minigrid project design	Minigrid developer	Project sponsors and financiers	Engineering, procurement, and construction contractors	Minigrid end-users
Monitoring and evaluation	5. Monitor and reassess resilience measures guided by an O&M and emergency response strategy	Minigrid developer	Project sponsors and financiers	Community leaders	Minigrid end-users

This Section details key issues for each of the three phases and provides a step-by-step guide with relevant case studies to improve minigrid resilience. Although the variability, characteristics, and severity of climate change impacts are project-specific, the resilience framework and resources for integrating climate risks across the phases of minigrid project development can be applied to different projects.

The amount of time needed to complete an assessment will vary based on a range of factors, including existing expert knowledge of climate change in the country more broadly and the community in particular, local awareness of climate change impacts, and experience of the minigrid developer in conducting similar assessments.

Tools to integrate climate resilience in minigrid development

This section provides guidance on the information and tools needed to integrate climate resilience in minigrids across the three phases — planning, procurement and execution, and monitoring and evaluation.

4.2 Minigrid project planning

Developing a minigrid project plan involves establishing the energy needs of a given community. The developer typically initiates this by identifying and engaging potential customers seeking reliable power. It also involves the identification of an appropriate site for the minigrid generation and distribution assets.[viii] Although activities that help to reduce vulnerability, such as flood-resilient building and rainwater harvesting, are gaining traction across the energy sector, adaptation in minigrids is not gaining momentum fast enough to keep up with the rate at which climate change is impacting rural African communities.

Building climate-resilient minigrids requires incorporating climate change considerations along with other project planning and risk parameters, such as financial, technical, and commercial feasibility, in the planning phase of a minigrid. Minigrid planners should consider both near-term climate variability and long-term changes in climate and associated impacts on end-users. The benefits of proactively evaluating and building resilience to climate impacts up-front typically mitigate the impacts to both the minigrid project and the community. Usually, these evaluations are already conducted as part of the development of social and environmental safeguards assessments. For instance, UNDP's Social and Environmental Standards includes a standard on Climate Change and Disaster Risks that needs to be complied with for UNDP projects.[31] An illustration of how these risks are considered through the Environmental and Social Impact Assessment (ESIA) study for minigrids is shown below.

[viii] This process involves detailed customer enumeration and site selection.

Environmental and Social Risk Assessment for AMP Minigrids

To align with UNDP Social and Environmental Standards (SES) and national legislation, the AMP requires that all minigrids undertake a screening and assessment to ensure that environmental and social risks associated with the installation and operation of the minigrid have been identified, assessed, and managed. This is usually done through an Environmental and Social Impact Assessment (ESIA) and Environmental and Social Management Plan (ESMP) for each minigrid. One of the identified risks is the vulnerability of the minigrid to climate change and climate-induced and natural disaster risks, such as flooding and earthquakes. UNDP's Guidance Note on SES demonstrates how these risks can be assessed and mitigated through adaptive design and other management measures.

4.2.1 Understand exposure to climate hazards

The first step to incorporating climate resilience into minigrid project planning is understanding the extent to which the local community is exposed to climate change impacts. This step is crucial in gathering useful information on climate risks affecting the local community, and the local communities' climate change vulnerability and adaptive capacity. This enables the consideration and integration of appropriate adaptation measures right from the beginning of the project. It also creates an enabler to incorporate climate risks, vulnerability, and adaptive capacity in the next phase of the project development cycle — the project design. The minigrid developer should engage with residents to understand previous climate incidents such as floods and windstorms. The community engagement activities will enable the minigrid developer to profile potential minigrid locations across different communities based on the history and frequency of adverse climate impacts.

In addition to understanding historical climate impacts, it is important for minigrid developers to ascertain the possibility of unobserved impacts. For instance, Madagascar, Mozambique, southern Zambia, northeast Zimbabwe, and Malawi had not experienced a cyclone in centuries prior to Cyclone Freddy, which is described as "one of the worst tropical cyclones on record" in strength, length, and resurgence.[xxv] Predictions on extreme weather events from publicly available sources, including the World Meteorological Organization (WMO) and NASA, can be obtained and analyzed.

The aim of this first step is to gain an understanding of the context in which the minigrid would be developed. This can be achieved by developing a climate hazard exposure matrix to identify how the minigrid and community are exposed to climate change using data collected from key stakeholders, such as local government authorities, during stakeholder engagement processes. Climate hazard exposure matrix, an example of which is given in Appendix B, can be used to:

- Understand the characteristics of the landscape of the local community, such as the topography, geology, climate, land cover, land use, and natural resource availability;
- Evaluate and understand the interrelationships between different factors that are likely to affect the minigrid and the community's exposure to climate shocks;
- Build baseline data for the economic conditions and revenue-generating sources of the community; and
- Identify challenges related to resources and people that influence electricity demand.

Steps to understand exposure to climate hazards

1. **Collect data:** Building resilient minigrids should be data-driven, based on evidence and robust information and knowledge
    a. Collect climate change data about historical and future climate changes, vulnerabilities, and impacts on the region from publicly available sources including the World Meteorological Organization (WMO), NASA, the World Resources Institute, and the World Bank;
    b. Identify ongoing activities in the community with relevance to climate change adaptation and mitigation (building resilient minigrids should not be done in isolation but coordinated with ongoing activities).
2. **Identify climate hazards from the community.** Identify key stakeholders in the community and conduct a survey to understand the community's exposure to climate hazards. The following guiding questions can be used.
    a. What are some climate change impacts that have affected your community in the past?
    b. How frequently do these climate change impacts/hazards occur?
    c. What are some climate change impacts that are currently affecting your community?
    d. What are some climate change impacts that may affect your community in the future?
    e. What are some climate and non-climate-related stressors the community has experienced/is experiencing?
    f. Are there specific areas within the community that are more vulnerable to certain hazards?
3. **Evaluate exposure**
    a. Make a detailed list of infrastructure, commercial activities, and natural resources that the community depends on to keep functioning.
    b. Use the information gathered to complete the climate hazard exposure matrix template provided in Appendix B.

4.2.2 Assess and rank vulnerability and risk

The high uncertainty in data makes it challenging to establish causal relationships between climatic conditions and hazards, exposure, and vulnerability factors. Most climate risk tools therefore adopt indicator-based vulnerability and risk assessments using data of climatic events and climate projections collected from existing sources, surveys, and stakeholder engagements to assess the likelihood and consequence of a climate risk happening.

While several climate risk screening tools have been developed by different organizations, their differing purposes and the fast-evolving nature of climate change impacts and available data make it difficult to have a single right tool. A selection of tools suited for climate screening is presented in Table 5.

Table 5: Publicly available climate risk screening tools

Resource name	Provider	Summary	Primary user
Climate and disaster risk screening tools	World Bank	Developed for use by development practitioners for both in-depth and rapid screening of short- and long-term climate and disaster risks to build resilience at an early stage of project design.	Energy project developers
Climate risk screening and management tools	USAID	A set of tools that helps users improve the effectiveness and sustainability of development interventions by assessing and addressing climate risks.	USAID project planners
STAP guidance on climate risk screening	GEF	The tool proposes a common standard for a climate risk screening process that includes four steps: hazard identification, assessment of vulnerability and exposure, risk classification, and a risk mitigation plan.	GEF Agencies
Climate vulnerability and capacity analysis	CARE	A community-level tool used to gather and analyze information on community-level vulnerabilities to inform actions to increase resilience. It is a 7-step process that details a set of guiding questions on climate risks and resilience.	Project managers in development organizations
Climate change and environmental degradation risk and adaptation assessment (CEDRA)	TearFund	An environmental risk assessment tool that helps identify and assess past, present, and projected impacts of climate change, the likelihood of these impacts occurring, and their likely scale of impact. It provides action plan templates for integrating resilience measures.	Humanitarian and development agencies
Climate Alignment, Impact, and Risk Toolbox	RMI	A tool to help financial institutions identify and access different types of tools, frameworks, and platforms available to measure and report their climate-related alignment, impact, and/or risk.	Financial institutions

VIDA	VIDA	A geospatial modeling tool that assesses climate risks, tracks their impact, and helps organizations meet reporting requirements. The tool includes location-specific data on climate risks, biodiversity, environmental markers, social and governance conditions, and renewable energy potential.	Developers and financiers

Madagascar case study

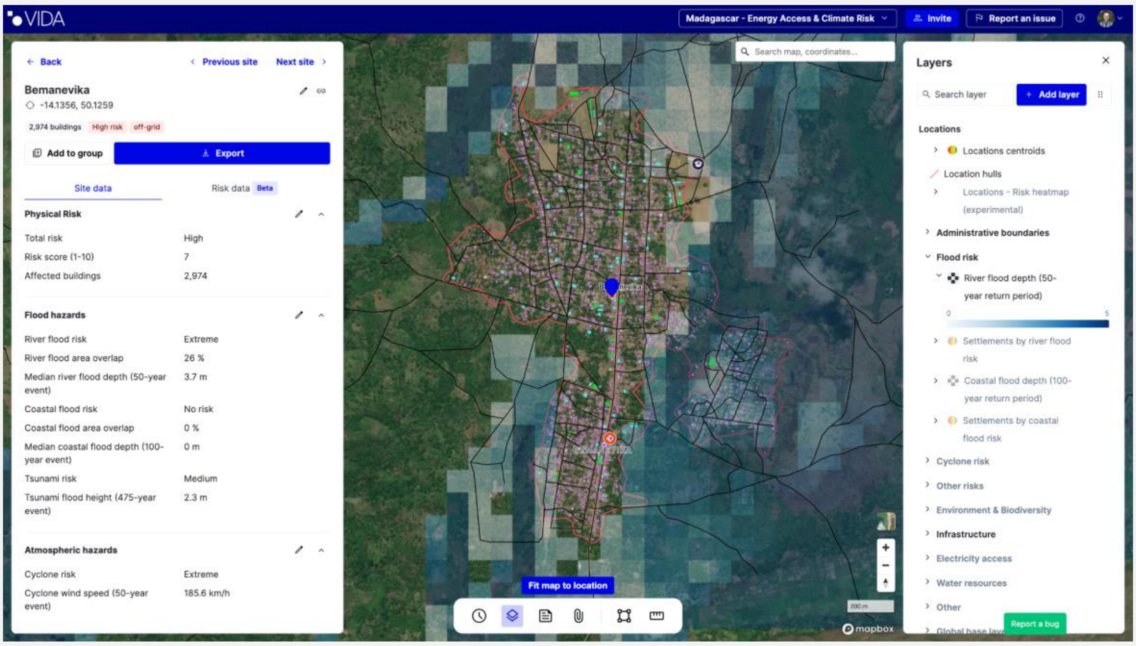
A geospatial approach to integrating climate risk into minigrid project planning

In 2024, the geospatial platform, VIDA, partnered with the World Bank to pilot a climate-informed energy planning approach in Madagascar, one of the countries most at risk from climate change due to its topography, location, and socioeconomic conditions.

VIDA identified and assessed 3,400 communities with potential minigrid sites using more than 50 indicators, including building counts, electricity access, energy demand, and socioeconomic characteristics. To enable climate-informed planning, VIDA layered in historical and projected data on high-priority hazards including river and coastal floods, droughts, cyclones, and wildfires. Each community received exposure scores on a scale from 1 to 5 scale, which were then aggregated into a single index.

The final output was an interactive web-based platform that enables planners to visualize and filter communities based on specific criteria such as high exposure to flooding. This tool empowers decision-makers to prioritize sites for climate-resilient energy investment, enabling policymakers and minigrid planners to account for both exposure and socioeconomic vulnerability at the earliest stages of project design.

Below is a detailed settlement-level view that shows that several areas of this potential minigrid site are highly exposed to river floods.

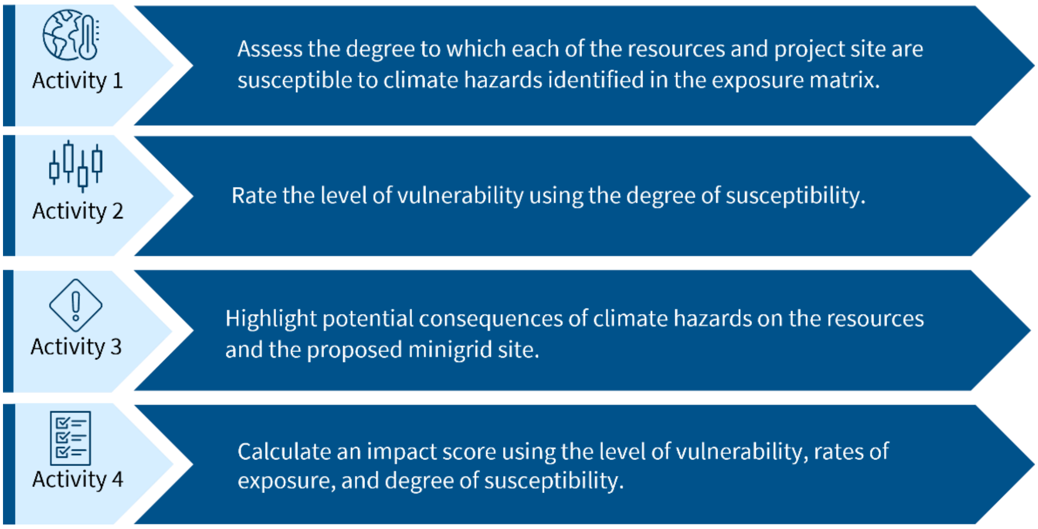


Source: VIDA

We recommend a four-step process for measuring vulnerability and climate risks over the life of the project to develop a vulnerability and risk characterization matrix. To inform decision-making purposes on resilience measures, the assessment must be made over the entire project life, from initiation through decommissioning, as climate risks can occur at different points in time.

The process involves systematically assessing the degree to which key resources, including the proposed minigrid project site, are susceptible to disruption from various hazards and climatic conditions identified in the exposure matrix. Below are the recommended steps in developing a vulnerability and risk characterization matrix.

Exhibit 6: Step-by-step guide to develop a vulnerability and risk characterization matrix



This process of assessing and ranking vulnerability and risk provides a high-level snapshot of the likelihood of a climate risk happening and the degree of impact it is likely to have on the community's economy-reliant resources and proposed minigrid sites. Table 6 provides a template for developing a climate vulnerability and risk characterization matrix.

Table 6: Climate Vulnerability and Risk Characterization Matrix

Key resource	Climate hazard	Exposure	Degree of sensitivity	Vulnerability	Likelihood of occurring	Potential consequences	Impact
Farm	Flooding	High	High	Dredging waterways from a river	High	Destruction of low-lying farmlands Power disruption	High
Community center	Heat wave	Medium	High	Mass cooking in a building	Low	Sudden and sustained increase in electricity demand	Medium
School	Flooding	High	Medium		Medium	Destruction of school roof Power disruption	Medium

When developing a climate vulnerability and risk characterization matrix, it is important to integrate any evidence gathered or assumptions made to reduce the level of subjectivity in the outcome of the assessment. Key areas where further investigation may be required should also be noted.

Based on the outcome of the assessment, an impact-risk matrix can be developed to depict the range of climate hazards identified (see Exhibit 7). Climate hazards in the green zone are low risk, while those in red have the highest likelihood and impact of risk and should be prioritized when developing resilience measures.

Exhibit 7: Impact-Risk Matrix

Likelihood of risk	Potential Impact 1	Potential Impact 2	Potential Impact 3
3	High	Substantial	Substantial
2	Moderate	High	Substantial
1	Low	Moderate	High

4.3 Project procurement and execution

Project preparation, the second phase in the project development cycle, involves conducting technical assessments and designing the minigrid. The results from the vulnerability and risk assessment matrix form the basis for designing the project in a way that makes its components resilient to climate impacts.

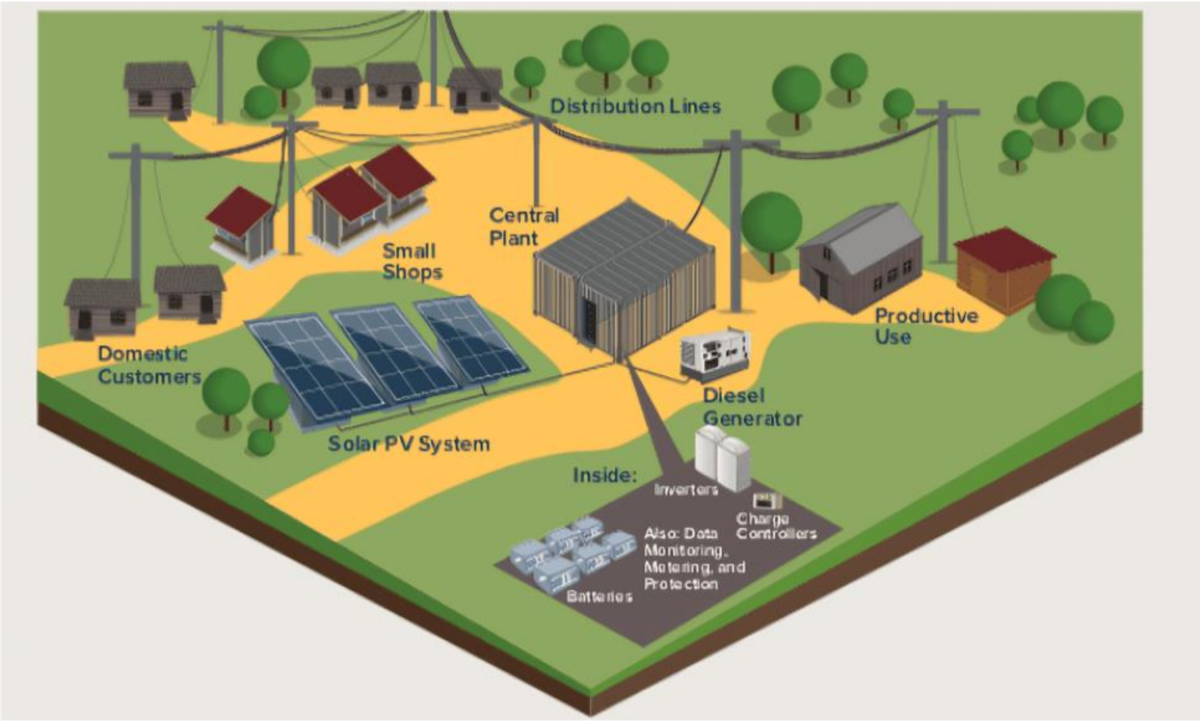
Expanding on climate change impacts on minigrids outlined in Section 1, this section details the impacts on different components of a typical minigrid solution and highlights resilience measures that can be adopted to address these impacts. For this toolkit, it is assumed that minigrid developers are already equipped to achieve the broad objectives of project design, including energy resource assessment, system sizing and configuration, and interconnection processes.

4.3.1 Identify technical resilience measures

This toolkit focuses on a typical renewable energy minigrid asset consisting of four main components — primary generation source (e.g., solar panels), distribution lines, energy management system, and battery energy storage system. Exhibit 8 illustrates how these components connect. Climate change can impact these individual components and affect their performance, leading to efficiency losses, potential damages to the assets, and overall poor performance of the minigrid. It is important to note that minigrids can be operated independently from the main grid or interconnected with the grid.

In designing the minigrid, the climate risks identified during the vulnerability and risk assessment should be assessed against project outputs to ensure that associated threats to the project and community are factored into the project's technical and commercial feasibility.

Exhibit 8: A typical solar PV minigrid



Source: RMI

Climate change can have both short-term and long-term impacts on the minigrid. Short-term impacts are those that directly affect the electricity supply within a short period of the climate event, such as damage to solar PV panels from extreme events and increased demand for cooling from rising temperatures. Long-term impacts are those that occur over longer periods, such as variations in solar radiation from increasing cloud cover. Long-term climate impacts are enabled by both climate and non-climate stressors. An example of a climate stressor is an increase in the frequency and intensity of precipitation, which can lead to flooding. A non-climate stressor could be an increased risk of flooding due to erosion caused by frequent sand winning.[ix] Climate change is expected to increase existing stressors for minigrids, including higher temperatures, changes in solar radiation, and more frequent and intense weather extremes.

Mitigation planning is a key step in ensuring the resilience and sustainability of minigrid sites. It involves identifying risks and developing resilience measures and strategies to mitigate the risks while identifying the required resources for implementation. Tables 7 to 10 provide details on the impacts of climate hazards on the four minigrid system components and highlight key resilience measures that can be implemented to mitigate the impacts. Although minigrid developers are already implementing resilience measures as illustrated by the case studies, minigrids can be made more climate-resilient when climate considerations are accounted for in each component.

[ix] Sand winning refers to the extraction of sand, often from natural sources like riverbeds, beaches, or dunes, for use in construction and other industries.

Component 1: Primary generation source — Solar PV panels

Electricity supply from solar photovoltaic (PV) panels is highly dependent on weather conditions such as rainy days, solar radiation, and cloud cover, all of which are subject to climate change impacts. Solar power output will therefore vary based on climate change impacts. A recent study estimates that solar output will decline by up to 8% from climate change impacts if resilience measures are not incorporated.[32]

To withstand weather changes, there is a need to incorporate the uncertainty caused by changes in climatic conditions in solar PV minigrids. Table 7 outlines the impacts and resilience measures for solar panels that should be considered in designing climate-resilient minigrids.

Table 7: Climate change impacts on solar panels

Climate hazard	Impact	Resilience measures
Increasing temperature	• Reduced efficiency and lifespan of panels due to delamination and damage • Reduced solar PV capacity	• Install minigrids with additional capacity in solar panels to make up for losses
Rainstorms and winds	• Reduction in capacity due to transient dust • Damage to panels	• Avoid building minigrids near steep slopes and next to trees with branches that could damage the panels in case of a rainstorm • Increase solar PV panel cleaning and maintenance
Flooding from sea level rise or overflowing rivers	• Damage to panels including breakages	• Protect from exposure to floods by assessing potential sites' flood-risk levels • Elevate panels above the ground and construct proper drainage systems
Lightning	• Damage to panels • Power surges	• Install lightning arrestors[x]
Prolonged cloud cover	• Reduced output	• Increase system capacity to compensate for reduced efficiency during long periods of cloud cover

[x] Devices that arrest/contain lightning to prevent damage to the system.

India case study – Minigrid resilient to extreme heat

Rajasthan, a state in India, has been experiencing heatwaves in recent years. To mitigate the impact of extreme heat and frequent cloud covers, minigrid projects in Rajasthan are installed with 30% excess capacity to ensure optimal output due to efficiency losses that affect solar panels and the battery energy storage system.

Source: World Resources Institute, 2019[33]

Component 2: Power distribution lines

The majority of power distribution lines are constructed as overhead power cables on distribution poles. Climate change impacts on power distribution lines can result in power outages to consumers either through a direct impact (such as damage to a power cable due to extreme rain and sun) or an indirect impact (such as trees falling on power cables). This also results in additional maintenance costs for minigrid operators. Table 8 outlines potential climate change hazards to power distribution lines and corresponding resilience measures to mitigate the impact of such hazards.

Table 8: Climate change impacts on power distribution lines

Climate hazard	Impact	Resilience measures
Increasing temperature	• Reduced line capacity • Sagging power lines due to aluminum or copper expanding with heat, making it dangerous for the public • Fire damage to distribution lines from increased wildfire risk	• Install high-power line poles • Install conductors with hotter operating limits • Use high-temperature, low-sag conductors[xi] • Consistently clear vegetation around distribution lines and create fire-defensible space • Use fire-resistant materials for constructing poles • Create firebreaks
Rainstorms and winds	• Destruction of lines and power disruptions	• Don't plant trees along distribution poles • Strengthen the structural integrity (e.g., make them thicker or use different

[xi] High-temperature low-sag (HTLS) conductors are designed to maintain high power transmission capacity and minimal sag at elevated temperatures, using advanced materials and designs like aluminum-zirconium alloys or composite cores.

		material) of line fasteners to mitigate system disruptions[xii]
Flooding from sea level rise or overflowing rivers	• Inundation of low-lying distribution poles • Decomposing of poles (especially when they are made of wood)	• Build distribution network outside of flood-risk zone if possible • Use a material other than wood for the lower parts of distribution poles
Lightning	• Damage to distribution lines • Power surges	• Install lightning arrestors

Component 3: Energy management system

Energy management systems are included in minigrid facilities to primarily measure, monitor, and control electrical loads to optimize their performance. For instance, smart metering infrastructure allows minigrid operators to collect data on consumers' consumption patterns to inform operational and expansion decisions. Similarly, charge controllers installed between the solar panel and the battery storage system prevent overcharging of the batteries. Protecting the energy management system from climate impacts such as flooding and lightning is critical to ensuring the optimal performance of the minigrid system.

Table 9: Climate change impact on energy management system

Climate hazard	Impact	Resilience measures
Increasing temperature	• Overheating of electrical appliances • Reduced line capacity resulting in sub-optimal system management	• Use component material specifications that adapt to temperature sensitivity • Implement measures to protect equipment from extreme temperatures, such as insulation, ventilation systems, and shading structures (e.g., planting trees)
Rainstorms and winds	• Destruction of computer systems and other electrical appliances	• Ensure that buildings that house computer systems are built away from storm paths • Improve the structural integrity of the buildings and use materials and construction techniques that enhance the wind resistance of buildings

[xii] Line fasteners anchor the line to the ground.

Flooding from sea level rise or overflowing rivers	• Power disruptions • Loss of data	• Incorporate lightning arrestors in buildings where the energy management system is housed from power surges
Lightning	• Destruction of computer systems and other electrical appliances	• Install lightning arrestors

India case study – Minigrid resilience to lightning and thunderstorms

Jharkhand, a state in India, is piloting climate-resilient minigrids. Thunderstorms and lightning are the key climate risks that affect the state. They cause frequent power outages when falling trees and lightning strikes grid infrastructure to the detriment of community health centers in the state.

To address this, a climate-resilient minigrid has been developed in Gumla, a suburb of the state. The minigrid has lightning rods, surge protectors, and chemical earthing to serve as precautions against thunderstorms.

Source: World Resources Institute, 2019

Climate change, especially rising temperatures, also has an impact on electricity demand. The International Monetary Fund (IMF) estimates that a 1°C increase in temperature in sub-Saharan Africa is estimated to increase electricity demand by 6.7% on average.[34] To address this impact, minigrid developers should factor in a potential increase in demand when sizing minigrids. Additionally, developers should create awareness and build capacity among consumers on the use of energy-efficient appliances.

Component 4: Battery storage

Battery storage is a critical component of minigrids, ensuring reliability of supply by storing excess energy generated during periods of low demand and supplying the energy during high-demand periods. For interconnected minigrids, batteries and inverters must be configured to operate in the event of a grid outage. Similar to solar PV panels, climate impacts can have adverse effects on battery storage systems. For instance, very high temperatures can potentially overcome the cooling systems within the batteries to the extent that they can initiate a chemical reaction in the batteries known as thermal runaway. In extreme cases, thermal runaway can lead to both fire and explosion, posing physical harm and financial risks to the minigrid operator. Table 10 outlines potential climate change hazards and corresponding resilience measures to mitigate the impact of such hazards.

Table 10: Climate change impacts on battery storage

Climate hazard	Impact	Resilience measures
Increasing temperature	• Reduced efficiency and lifespan of battery energy storage systems • Can lead to an explosion and fire in worst-case scenarios	• Implement cooling technologies such as air conditioners and fans, or enhance ventilation to increase the efficiency and lifetime of battery cells • House batteries and power electronics in thermally isolated enclosures or buildings • Passive cooling strategies, such as locating solar PV module structures to create natural shade on the battery housing • Ensure the battery system is free from humidity
Rainstorms and winds	• Damage to batteries and electrical components	• Ensure batteries are sited away from storm paths • Install batteries at a higher level away from the ground, build a casing and drainage around the battery storage system
Flooding from sea level rise or overflowing rivers	• Damage to batteries	• Sufficiently protect sites prone to flooding by building drainage and flood barriers
Lightning	• Destruction of batteries from a power surge	• Install lightning arrestors
Prolonged cloud cover	• Reduced output	• Through modularity and planning, right-size minigrid components to ensure a continuous electricity supply during prolonged cloud cover

The variability, characteristics, and severity of the impacts of climate change vary across different communities and ultimately inform the combination of climate hazards and stressors inherent to a given location. Consequently, the different combinations of hazards and stressors determine the choice of resilience measures implemented for any given minigrid project. It is recommended that minigrid developers select resilience measures that are low-cost and that optimize the anticipated benefits to develop a mitigation plan.

4.3.2 Integrate resilience measures into minigrid project design

Having identified a set of resilience measures, minigrid developers should compare the effectiveness of these measures in mitigating climate hazards, cost trade-offs, and their resultant reliability on the minigrid solution, which can vary widely between different markets. For instance, developers should ascertain if it is more cost-effective to use low-cost cooling technologies to increase panel efficiency or to increase the sizing of certain components. Additionally, the benefits of implementing these measures on the system's overall performance and commercial feasibility should be accounted for.

The resilience measures should guide equipment purchase and other procurement activities. The costing and financing of minigrids should therefore not be finalized until all resilience measures are incorporated. Malawi's 12kWp Mthembanji solar PV minigrid (see Exhibit 9) is an example of a resilient minigrid.[35] Climate considerations incorporated in the minigrid to ensure its resilience to climate hazards, particularly floods, included high pole mounts to allow free-flow of floods, and lightning arrestors. As a result, the minigrid still stands despite the severe flooding it has faced since it began operating in 2020.

Exhibit 9: Climate-resilient Mthembanji solar PV minigrid

Source: Community Energy and Sustainable Energy Transitions, 2024

Furthermore, minigrid developers should build flexibility into minigrid designs, such as building smaller modular units. This makes minigrids easily adaptable to system upgrades when weather patterns change in the future. This is because the exact nature of climate change impacts on the lifetime of a typical minigrid project is uncertain.

Integrating climate resilience measures into minigrids can have significant impacts on their cost structure by increasing capital and operational expenses. This is due to the need to ensure resilience through enhanced system reliability, redundancy, and robust infrastructure capable of withstanding extreme weather events. For example, ensuring about 100% availability for a solar PV and battery storage minigrid can increase capital costs substantially, as it will require larger battery storage, more resilient components, and oversizing the solar panel capacity.[36]

Preliminary findings from AMP's ongoing Derisking Renewable Energy Investment (DREI) interviews in Madagascar show that while these costs are not evident in financing costs, they are clearly seen in capital expenses. Additionally, developers are already pricing the cost of resilience measures in the implementation of the projects by increasing end-user electricity tariffs. Minigrid developers should therefore consider trade-offs between cost increases and enhanced resilience.

It is estimated that reducing availability targets to around 80% and investing in energy efficiency measures can lower costs by about 65%. This makes the minigrid more affordable while still improving resilience. For a minigrid in New Mexico, for instance, reducing availability to 80% over a 48-hour islanding period and incorporating energy efficiency retrofits reduced the minigrid costs by up to 70%.[37] Ultimately, minigrid developers need to assess a combination of resilience measures to determine the ones that offer the most resilience at the least cost. In the long term, the increased costs from resilience measures are often offset by the long-term benefits of reduced vulnerability to climate-related disruptions and increased reliability.

Practical Action, on behalf of GOGLA (the global association for the off-grid solar sector), has produced a set of resources to support more intentional use of off-grid solar technologies (solar home systems, solar-powered appliances, and other stand-alone systems) to enhance climate resilience and adaptation. These are aimed at off-grid companies, impact investors, donors (including the four climate funds), governments, NGOs and other development actors.

The resources and accompanying report *Off-Grid Solar: Powering Climate Resilience* explore the contribution of off-grid solar to resilience and adaptation across four impact areas:

The two resource are:

1. The Off-Grid Solar Resilience and Adaptation Framework to help users understand, measure, and evaluate the contribution of technologies:
    - Measurement Resource: A compendium of resilience and adaptation measurement indicators and guidance, grouped by key impact areas.
    - Global Dashboard: A set of framing indicators grouped by impact area that can be used to track contributions by technologies at regional, national, or international levels.

2. The Off-Grid Solar Resilience and Adaptation Sector Guidance to support users to design and implement off-grid solar business models, projects, and programs more intentionally to enhance climate resilience and adaptation in line with best practices.

The resources and accompanying report were developed with the support of the IKEA Foundation and Efficiency for Access Coalition and can be accessed via GOGLA's website:

https://gogla.org/climate/resilience-adaptation/

Source: Practical Action

4.4 Project implementation and operation

The project implementation phase is where the minigrid developer finalizes and signs all project agreements and constructs the minigrid system along with any distribution network upgrades. After finalizing the project design, minigrid developers must ensure strict adherence to resilience measures identified during the project preparation phase. Minigrid developers must also ensure that procurement processes align with the resilience measures. Finally, it is important to engage key stakeholders that can support the implementation of identified local climate strategies, such as awareness creation and capacity building among local residents.

4.4.1 Align minigrid operation with O&M and emergency response strategy

Implementing climate risk considerations in minigrids does not necessarily ensure that the minigrid is devoid of climate hazards. Particularly in communities with frequent extreme weather events, a lack of an effective operations and maintenance (O&M) strategy that incorporates emergency response strategies can lead to partial or total destruction of the minigrid assets.

Minigrid developers should ensure that the project team or relevant body is well-equipped to respond quickly to emergencies without disrupting project activities. Additionally, there should be clarity of roles and responsibilities for emergencies as they arise. The lack of operational clarity of roles and responsibilities among minigrid developers, the utility, the local community, and other stakeholders can result in delays in responding to climate hazards. Therefore, responsible parties must be well-informed and equipped to respond to climate hazards.

Below is a checklist to guide developers in developing a climate-oriented O&M strategy.

O&M strategy checklist

- ❑ The O&M strategy includes the identification of early warning signs for hazards affecting the minigrid and local community.
- ❑ A contingency plan is in place to respond to emergencies with the least disruption to minigrid operations.
- ❑ The O&M strategy includes monitoring of climate risk parameters identified during the design stage.
- ❑ The project implementation plan identifies the social, political, and economic context that may have implications for climate change.

The ability of minigrid developers to prepare for, respond to, and recover from extreme weather events and climate change is critical and should be incorporated in the O&M strategy.

4.4.2 Monitor and evaluate

Monitoring the performance of minigrids is essential for gathering valuable data and insights to understand and develop early warning systems to protect minigrids and the communities they serve from adverse impacts. It is critical to address environmental, technical, commercial, and social concerns as they arise to ensure the sustained performance of the minigrid. Evaluation is the process of analyzing monitoring data to understand the extent of impact any arising issue may have. Minigrid operators must monitor the vulnerability of the minigrid site to the adverse climate change impacts identified during the planning phase, as well as monitor resilience measures implemented at the execution phase to ensure the long-term resilience and effectiveness of the system.

Monitoring and evaluating a minigrid's exposure to climate risks must be integrated into the overall performance monitoring framework. Climate risk monitoring processes must be robust and conducted throughout the life of the project. For instance, it is a best practice to monitor minigrid performance, including supply hours and interruption indices at regular intervals, accounting for both technical issues and stakeholder perceptions, and compare with baseline data collected during the minigrid planning phase. Monitoring climate hazards could either be direct or indirect. Direct climate hazard monitoring involves repeated direct technical observations of climate hazards, such as visiting landslide sites and measuring wind speeds at a minigrid site. Indirect climate hazards monitoring involves periodic monitoring of data collected through data loggers and mechanisms for community feedback, such as through in-person stakeholder consultations.

This toolkit outlines a three-step monitoring process:

1. **Establish monitoring systems:**
    - **Community engagement**: Involve community members in monitoring local weather patterns and reporting unusual events. This ensures real-time, ground-level data collection and strengthens community participation in climate resilience efforts.
    - **Data storage and analysis**: Set up a robust system for storing and analyzing collected data. This system should identify trends and forecast potential threats, and support decision-making. The system can include rain gauges to measure rainfall intensity, anemometers to measure wind speed, and thermometers to measure temperature.
    - **Visual observations**: After a climate event happens, visit the relevant sites to assess the impact of the event and measure against any available information, including early warning signs.

2. **Monitor hazard activity:**
    - **Climate trends**: Analyze collected data to monitor changes in average temperatures, precipitation patterns, and extreme weather events. Use this analysis to forecast potential climate impacts and inform proactive measures.
    - **Visual inspections**: Conduct regular visual inspections of minigrid infrastructure to detect signs of wear and tear, which may be exacerbated by climate hazards. Establish a checklist for inspections and ensure timely maintenance and repairs.

3. **Re-assess climate risk:**
    - **Frequency**: Re-assess vulnerability and risk characterization matrices regularly, especially after significant climate events. This should be a systematic process to ensure the ongoing relevance and accuracy of the risk assessments.
    - **New data**: Update the risk assessments with new data from monitoring systems and the latest climate projections. Ensure that these updates are integrated into the overall risk management strategy.
    - **Adaptation strategies**: Evaluate the effectiveness of existing adaptation strategies in light of changing risks and adjust them as required. Make sure the strategies reflect both new risk data and community feedback.

By actively engaging community members, utilizing comprehensive data systems, and maintaining regular oversight of infrastructure, minigrid operators can effectively monitor and mitigate climate hazards. Continual reassessment and adaptation of strategies ensure that the minigrids remain resilient and capable of supporting sustainable development in rural communities, even in the face of the challenges posed by climate change.

4.4.3 Explore climate risk insurance instruments

Climate risk insurance for minigrids in Africa is an emerging financial tool designed to enhance the resilience of minigrids against climate change impacts. Climate risk insurance tools help mitigate climate change risks by offering financial protection that enables minigrids to recover quickly from climate disasters and continue to provide electricity. This financial protection transfers the risk of extreme weather events from minigrid operators to insurers, by providing timely payouts to developers in the event of a risk that is covered by the insurance policy. Additionally, climate risk insurance can increase investor confidence in minigrids due to the reduction in perceived risks in minigrids.

The African Risk Capacity (ARC) drought insurance scheme in Malawi, although not designed specifically for minigrids, is an example of a climate risk insurance tool. The ARC was designed as part of a sovereign drought insurance policy to provide rapid financial resources to mitigate the impacts of climate shocks. For instance, in response to the severe drought caused by El Nino in Malawi in 2023, the ARC provided over $11.6 million to Malawi's government to support food assistance and cash transfers to households affected by the drought, helping to stabilize livelihoods and support recovery efforts. This example demonstrates how climate risk insurance can be used to enhance resilience in critical sectors beyond agriculture, like minigrids, by ensuring quick access to funds that enable continuous operation and disaster recovery.

5. STRENGTHENING COMMUNITY RESILIENCE TO SUPPORT CLIMATE-READY MINIGRIDS

Integrating climate considerations into a minigrid without improving the community's resilience to climate change impacts can affect the sustainability of the minigrid. As a result, a minigrid's vulnerability to climate change impacts goes beyond the minigrid itself. For instance, very poor rural communities are more vulnerable to climate change impacts because they are more likely to lose their entire livelihood during a climate-related disaster, making it challenging, if not impossible, for them to pay for electricity. In this regard, minigrid developers should be incentivized to partner with other stakeholders, such as local government agencies, to create awareness among rural communities on strategies to enhance the resilience of rural communities to climate change. These practices could include agroforestry, conservation agriculture, certified seeds, adoption of drought-resistant crops, implementation of solar irrigation systems, integrated pest management, and crop diversification.

Given that agricultural support services may fall outside the scope and competencies of minigrid developers, they must be incentivized to facilitate or conduct such activities. Similarly, minigrid developers can partner with agricultural extension service providers and financing agencies to support farmers by increasing their access to local weather forecasts, drought insurance, and climate-resistant crops.

The capacity of rural African communities exposed to climate risks to anticipate, mitigate, and recover from the effects of climate hazards without compromising on their ability to receive and pay for electricity from minigrids is critical to the sustainability of climate-resilient minigrids. This section discusses four key measures to build the adaptive capacities of rural communities to increase community resilience.[xiii]

Exhibit 10: Strategies to increase community resilience

[xiii] Adaptive capacity refers to the ability of a community to prepare for, respond to, and recover from a climate disaster.

While this toolkit does not include an assessment of the adaptive capacity of the local community, different organizations have developed tools and frameworks that are instrumental in understanding the climate resilience of rural communities. An overview of some of these tools, each offering unique methodologies and insights, has been provided in Appendix B. Collectively, these tools enable rural communities to better understand their vulnerabilities and foster adaptive capacity while aligning with broader development goals.

5.1 Build the capacity of local institutions and community leaders

One of the most effective ways to build community resilience to climate change impacts is by empowering the community to adapt to changing environmental and climatic conditions. This can be achieved by building the capacity of community leaders and creating awareness among local institutions on climate change-related issues.

Such capacity-building efforts can be initiated by either minigrid developers, development partners, or the local community, and should begin with an assessment of their understanding of climate change. This helps shape the training to meet specific needs. The training should include both formal sessions for community leaders and open town hall meetings. Equipping local leaders on climate change helps them to make informed decisions that increase their resilience to climate hazards.

In addition to community leaders and local authorities, community members must be informed about the impacts of climate change and the importance of sustainable practices. Community meetings, educational campaigns, and the use of digital platforms can be leveraged to disseminate valuable insights. For instance, farmers should be trained in climate-smart agricultural practices to ensure sustained productivity amid changing weather patterns. This is discussed further in Section 5.3.

5.2 Institute community-based disaster response teams

Establishing community-based disaster response teams is a proactive measure to enhance community resilience and ensure that the community is prepared to respond to and mitigate climate change impacts. The disaster response team will be tasked with developing community-focused disaster plans that will include early warning and emergency response to alert the community of impending climate threats such as floods. Working closely with minigrid developers, and through training and capacity-building efforts, the community-based disaster response team will leverage local knowledge and utilize relevant skills and resources to minimize climate change impacts. A step-by-step guide to establishing a community-based disaster response team is provided below.

1. **Identify a community-based disaster response team**: Minigrid developers are well placed to identify community members who will voluntarily create awareness about climate change and its impacts and will serve as the disaster response team for the community. The team should learn about the importance of disaster preparedness and be able to discuss that with the community at large. It is important to ensure diversity within the team, such as in age, gender, and social status.
2. **Train and build the capacity of the team**: Collaborate with development partners, NGOs, and local disaster management authorities to conduct training workshops for the disaster team. An assessment of the team's understanding of climate change, its hazards, and its impacts in the community should first be conducted to develop a targeted training module. Focus should be given

to leveraging technology to gather data on climate change trends and disseminate information on impending hazards.

3. **Develop an emergency response plan**: Minigrid developers should work closely with the local authorities and the disaster response team to develop a comprehensive emergency response plan tailored to potential climate hazards that could affect the minigrid and the community. In developing the plan, it is important to conduct a resource assessment to identify available resources such as communication platforms, internet accessibility, and susceptible infrastructure to better understand the potential scope of the response required. Also, the plan should clarify the roles and responsibilities of stakeholders during a disaster.

4. **Conduct regular simulation drills**: To assess the extent to which the community is prepared for climate hazards and test the effectiveness of the emergency response plan, it is essential to organize regular disaster simulation drills. It would be ideal to organize this in parallel with the minigrid's O&M team to synchronize their response strategy with that of the community. Such simulation drills also help identify gaps in preparedness that can be addressed ahead of time.

5. **Monitor and evaluate**: Establish a system for ongoing monitoring and evaluation of the team's effectiveness. Continuous gathering of feedback from community members, minigrid developers, local authorities, and other key stakeholders is vital to improve response strategies.

Ghana case study – Community-led climate action

A community in southern Ghana, Ketu South and Anloga Districts, has historically suffered from coastal erosion and sea-level rise, affecting their homes and infrastructure. To address this, the community leaders formed a disaster response team to engage the community and implemented measures that reduce their vulnerability to climate change impacts.

Since it was formed, the community-based team has:

- led the creation of water passages to limit the impact of sea erosion;
- established early warning systems to create vigilance among residents about impending coastal hazards to ensure timely evacuation and prevent potential loss of life;
- restored mangrove plantations; and
- raised awareness within the community to increase understanding of coastal hazards and the importance of preparedness.

Source: Africa Policy Research Institute, 2022[38]

5.3 Adopt climate-smart agricultural practices

Climate change is impacting agricultural productivity with increasingly erratic rainfall patterns and rising temperatures. As a result, rural African communities that are highly reliant on agriculture face heightened risks to food security and livelihoods. Given the reliance of rural communities on agriculture to pay for electricity received from minigrids, it is crucial to adopt climate-smart agricultural practices to strengthen resilience.

Climate-smart agriculture utilizes innovative and sustainable agricultural practices such as crop rotation and agroecology to improve productivity. Additionally, climate-resilient crops such as drought-resistant seed varieties help farmers withstand extreme weather events like droughts and floods. Promoting climate-smart agriculture also has the potential to reduce carbon emissions through sustainable practices such as organic farming and efficient livestock management. For minigrid developers who provide financing for PUE equipment as part of their business model, climate-smart agriculture can improve the financial viability and sustainability of PUE business models.

Liberia case study – Building community resilience to climate impacts and livelihood support through climate-smart small-scale farming

Climate change in Liberia is significantly affecting agricultural productivity and livelihoods. At the same time, traditional agricultural practices by Liberian farmers result in soil disturbance, deforestation, and carbon emissions (through slash-and-burn farming systems), which contribute to climate change.

To address this, Vosieda West Africa, with funding from the Swedish International Development Agency (SIDA), is implementing a four-year (2022–2026) Climate-Smart Agriculture Intervention Program to equip about 21,000 smallholder farmers with sustainable and regenerative farming practices in Nimba County, Northern Liberia. The project aims to strengthen communities' resilience to climate change through climate-smart agriculture.

Key expected results include improved land use and productivity, strengthened community resilience, reduced agriculture-based greenhouse gas emissions, and increased income generation of smallholder farmers.

Source: Vosieda West Africa, 2022[39]

5.4 Promote water resource management

Climate change impacts such as sea level rise, floods, and droughts increase salinity in groundwater, which affects the availability of freshwater for domestic use, agriculture, and minigrid operations (e.g., cooling of components, cleaning of solar panels, and other equipment). Optimizing water use in rural communities, therefore, plays a critical role in enhancing the resilience of minigrids and communities to climate change. For instance, the development of diversified water sources like drip irrigation or rainwater harvesting systems, wastewater recycling, and desalination ensures efficient use of water and reduces the community's dependency on a single water source — unpredictable rainfall or groundwater.

One relatively low-cost solution adopted by most communities is the use of water storage facilities such as reservoirs, cisterns, and tanks, allowing communities to store water when it is available for use in dry seasons. Promoting crops that are resistant to drought and well-suited to local water availability levels can also help ensure agricultural productivity in acute water shortage periods.

Minigrid developers should also work with the communities to undertake green infrastructure projects such as reforestation and wetlands restoration to leverage the natural ability of landscapes to absorb excess water to reduce flood risks. Finally, advanced technologies that enable real-time monitoring and efficient distribution of water resources can be implemented to help communities respond to changing climate conditions on time. These technologies use sensors and data analytics to detect leaks, optimize water usage, and respond swiftly to changing conditions.

Ghana case study – Increased resilience to climate change through water resources management and livelihood diversification

Across Ghana, the three northern regions (Northern, Upper East, and Upper West regions) are the most vulnerable to climate change and have the lowest adaptive capacity. This is due to the regions' heavy dependence of livelihoods on rainfed agriculture and unpredictable precipitation, which is greatly affecting communities. For instance, land degradation, high rates of erosion, small dams, and dugouts are reducing their water-holding capacity.

To address this, UNDP implemented a seven-year (2015–2022) program to enhance the resilience and adaptive capacity of the communities to climate impacts and risks related to water resources. It achieved this by improving the planning and management of water resources by rehabilitating 13 dams and establishing 24 agricultural processing schemes.

Source: UNDP[40]

In the face of climate change, training local leaders, creating an emergency response team, adapting climate-smart agriculture, and optimizing water resources are fundamental to enhancing the resilience of rural communities. These resilience strategies enable communities to adapt their ecosystems in ways that ensure sustainable livelihoods and improve the resilience of minigrid systems in the communities.

6. CONCLUSION

Globally, Africa stands as the most climate-vulnerable region, with climate change posing an escalating threat to the sustainability of its rural communities. While earlier sections outlined the specific impacts, this conclusion highlights their broader significance.

Minigrids, like any other energy infrastructure, are not immune to the impacts of climate change. Extreme weather events and long-term changes in temperature and precipitation can damage infrastructure, reduce efficiency, and undermine the efficiency and sustainability of minigrids. Therefore, it is essential to incorporate climate risk and resilience considerations into minigrid planning, design, and operation. Without such integration, minigrids will likely face revenue losses, increased energy costs, and operational challenges, ultimately compromising their long-term viability and the resilience of the communities they serve.

This Climate Risk and Resilience Toolkit is intended for use by minigrid stakeholders to integrate climate risks into minigrid development, emphasizing the importance of incorporating climate considerations at each phase of the project life cycle. And while climate-resilient minigrids are crucial, their sustainability depends on improving the overall climate resilience of the communities they serve. The ability of rural communities to withstand climate impacts without compromising their ability to afford electricity is essential to the long-term success of minigrids. Therefore, we also developed this toolkit to help stakeholders enhance community resilience by building the capacity of local institutions and community leaders, establishing community-based disaster response teams, adopting climate-smart agricultural practices, and promoting water resource management.

Finally, integrating climate considerations into minigrid development and improving community resilience are mutually reinforcing strategies. By adopting these approaches, minigrids can provide sustainable energy solutions and contribute to building climate-resilient rural communities across Africa. This toolkit aims to support that process by offering actionable guidance for both minigrid developers and community stakeholders.

APPENDICES

Appendix A: Definitions of key terms used

Table 11: List of key terms used in the toolkit

Term	Definition
Climate change	A change in the state of the climate that can be identified by changes in the average and/or the variability of its properties, and that persists for an extended period, typically decades or longer.[xiv]
Climate risk	This refers to the potential for climate change to have adverse effects on lives, livelihoods, health and well-being, economic, social, and cultural assets and investments, infrastructure, service provision, ecosystems, and species.[41]
Climate resilience	Potential or ability of a system, a community or an organization to develop adaptive capacity in response to the effects or impacts of climate change to better manage the associated risks and seize opportunities.
Productive use of energy or electricity	This refers to the utilization of electricity-powered solutions which support any economic activity, and which will leave the user with more income than the previously used solution if any.
Productive use appliances	These are technologies utilized in agricultural, commercial, and industrial activities that result in the direct production of goods or provision of services.
Original equipment manufacturer	This is a company that manufactures and sells products or parts of a product that their buyer, another company, sells to its own customers while putting the product under its own branding.
Business model	A company's plan for profitably doing business including target market, mode of operation, products, required investment and revenue generation.
Minigrids	This is a set of small-scale electricity generators and possibly energy storage systems interconnected to a distribution network that supplies electricity to a small, localized group of customers and operates independently from the national transmission grid ranging in size from a few kilowatts up to 10 megawatts.
Economic activities	An economic activity takes place when resources such as capital, labor, production technologies or intermediary products are combined to produce specific goods or services with the aim of making profit.

[xiv] Climate change as defined by IPCC

Appendix B: Resources for further reading

Table 12: List of resources for further reading

Title	Description	Author(s), Year
Performance Assessment and Resilience of Solar Minigrids for Sustainable Energy Access in Ghana	• This article assesses minigrid performance in Ghana, provides examples of analytical tools to determine resilience to climate risk, and offers useful recommendations to minigrid operators and other key stakeholders on ensuring minigrid reliability and sustainability in the context of climate change.	Adu-Poku A., G.S.K. Aidam, G.A. Jackson, K.E. N'tsoukpoe, J.J. Kponyo, A.Messan, O. Ikonn, W. Kwarteng, F. Kemausuor (2023)
Climate Resilience and a Just Energy Transition in Africa	• The report profiles countries in Africa based on their climate resilience, using social, economic, industrial, infrastructural, and institutional indicators. It also provides background on the impact of climate change on the continent.	African Development Bank, 2022
Minigrids and Climate Resilience	• This article provides information on specific climate risks inherent in minigrids and targeted mitigation strategies for minigrid operators to consider.	Resilient Energy Platform (2021(undated)

Appendix C: Climate hazard exposure matrix

Table 13: Climate hazard exposure matrix

Climate Hazard	History of climate hazards	Current climate hazard	Potential for occurrence in the future	Climate stressors	Non-climate stressors and trend	Exposure rating
Flooding						
Extreme temperature increase						
Incremental rainfall change						
Coastal erosion						
High wind speed						
Dust storms						

- Are you aware of any past, ongoing, or planned studies or projects on the topic of climate change in this community?
- What measures, if any, are already in place to improve adaptation?

Appendix D: Evaluating the adaptive capacity of a local community

Table 14: Tools for evaluating adaptive capacity

No.	Tool/Resource	Developer	Brief description	Use case
1	Local Adaptive Capacity Framework (LAC)	African Climate Change Resilience Alliance (ACCRA)	• Developed by the Africa Climate Change Resilience Alliance, the LAC tool evaluates the adaptive capacity of local communities through five dimensions: asset base, access to knowledge, institutions and entitlements, innovation capacity, and governance. • The tool emphasizes not only what resources communities possess but also how effectively they utilize them, making it highly relevant for rural settings where resource constraints are common.	The Care Climate Justice Centre used the LAC tool to evaluate the local adaptive capacity of two rural communities in northern Ghana
2	Climate Change Vulnerability and Risk (CRVA)	UN-Habitat	• CRVA evaluates, at a preliminary project stage, the climate risk and vulnerability of communities, as well as water infrastructure projects in communities. • The tool assesses how current and future climate hazards (such as temperature, rainfall, droughts, and floods) impact the broader community, as well as existing and potential water infrastructure projects in communities.	UN-Habitat worked on a vulnerability assessment of Nairobi's urban areas, identifying climate-related risks such as flooding and heat waves.
3	Community-Based Adaptation (CBA)	CARE International Climate Justice	• CBA focuses on empowering communities to lead adaptation strategies by combining local knowledge with scientific insights. • It promotes climate-resilient livelihoods, disaster risk reduction, and advocacy for systemic changes, addressing the underlying causes of vulnerability.	In Africa, CARE International's CBA has been used to assess climate vulnerability and adaptive capacity of communities in Mozambique, Niger, Kenya, and Ethiopia

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