

Article

Beyond Energy Access: How Renewable Energy Fosters Resilience in Island Communities

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Abstract: People, communities, and economies in small island developing states are extremely vulnerable to climate change, disasters, and other crises. Renewable energy can play an important part in building the resilience of these communities. Three case studies were conducted in Fiji (i.e., a grid-connected secondary school with roof-top solar PV and biogas, an off-grid community with solar home systems, and a farm that uses solar PV for irrigation) to demonstrate how renewable energy initiatives build community resilience. This study used the community resilience framework, RETScreen tool, information gathered from key informants' interviews, and secondary data sources to conduct qualitative and quantitative analyses. It found that seven community assets, i.e., human, social, cultural, financial, natural, built, and political assets, are enhanced, leading to an increase in absorptive, adaptive, and transformative capacities for these communities. Furthermore, current research shows that human capital is one of the key instruments in the adoption of new innovative technologies. The results from this study can be used by decisionmakers to promote and implement similar technologies in communities, which not only provide clean electricity and clean cooking energy for climate change mitigation but also build community resilience.

Keywords: solar photovoltaic; biogas; community energy systems; resilience; natural disasters; small island developing state; energy access



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1. Introduction

Access to affordable, reliable, and sustainable energy is crucial for the well-being and development of societies worldwide. It is recognized as a fundamental human right and plays a pivotal role in achieving the United Nations' Sustainable Development Goals (SDGs), particularly SDG 7, which aims to ensure access to affordable, reliable, sustainable, and modern energy for all [1]. In Figure 1, it can be seen that the sub-Saharan African and Pacific Island small states are regions whose access rates are below the world average, implying the need for significant development to ensure energy access for all. However, in regions around the world, the availability and accessibility of energy vary significantly between rural and urban areas, leading to disparities in the livelihoods of the population. In Ref. [2], the authors highlight that electricity access will positively affect social (health, education, habits, and social networks) and economic (income-generating activities, market production and revenues, and household economics) dimensions, while the socioeconomic status of households affects electricity access. Furthermore, ref. [3] shows that urban dwellers are more likely to adopt clean cooking energy technologies compared to their counterparts (rural dwellers) because wealth index, religion, household size, education and

sex of the household head, ethnicity, type of dwelling, mobile and internet access, residence, and status were all significant factors associated with the adoption of clean energy.

This study aims to explore the role of community energy systems (CESs) in building climate change resilience in small island developing states (SIDSs), specifically in Fiji. While energy is often seen as a mitigation factor and a sustainable development tool, this research focuses on its potential for adaptation. Recognizing the limited research on CESs in developing countries, this study addresses this gap by analyzing how CESs contribute to resilience in Fiji.

Community energy systems (CESs) are one of the means of addressing the accessibility issue, as well as of building resilience in local communities. These energy systems, along with other initiatives, such as health centers, schools, and agricultural cooperatives, promote the self-sufficiency of communities, facilitate the conservation of cultural legacy, and improve the overall standard of living [4]. It is imperative to define common terminologies related to community energy and resilience. The authors of ref. [5] define community as “a group of people who share a common physical environment, resources, and services, as well as risks and threats”. Community can also be defined in different contexts: community of place (geographical boundary), community of interest (people who share common interests), community of identity (a group of people with a shared sense of identity), and community of practice (a group of people who share a craft or profession) [6]. While community energy systems are defined as small-scale localized systems which produce heat and/or electricity that may be managed by or for the local people, they may be able to directly benefit these communities in other ways [7]. Furthermore, there are numerous environmental, economic, and social benefits of community-based heat and electricity generation [8]. Recently, the concept of community definition regarding energy systems was clarified by [9], a paper which shares 183 definitions found in the literature. Based on these different definitions, this paper defines community energy systems as “renewable energy technologies that are used by or shared by the group of individuals at a particular location which impacts their economic, environmental, social, political and infrastructural dimensions”.

Communities are exposed to shocks and stress. Shocks include conflict, illness, floods, cyclones, drought, etc., while stresses include price changes of commodities used in households and income generation if a household member is a seasonal worker [10]. The level of risk to a community, as shown in Equation (1), is a function of the hazards it faces, its vulnerability to the damaging effects of those hazards, and its capacity to cope with those effects [11]. So, the level of risk to a community is reduced if its capacity to cope is increased.

$$\text{Risk} = \frac{\text{Hazard} \times \text{Vulnerability}}{\text{Capacity to cope}} \quad (1)$$

Resilience focuses on the ability of a person to recover and adjust to different situations while effectively managing stress and shocks [12]. It gives people, families, communities, and systems the ability to proactively lessen future shocks and adjust to current ones. Hence, resilience is not a static state but rather a continuous process because one can never eliminate all risks [11]. Despite the various definitions available in the literature, ref. [13] highlights nine core elements that are present in community resilience definitions: local knowledge, community networks and relationships, communication, health, governance and leadership, resources, economic investment, preparedness, and mental outlook. Furthermore, three central capacities of resilience are discussed by [14]:

- (i) Persistence, or coping capacity, refers to the ability of resilient systems to cope with shocks and to restore well-being to current levels after the events.
- (ii) Adaptation, or adaptive, capacities are preventive actions that individuals or communities employ to learn from experience or to reduce the impact of predicted shocks.

The skills and resources required for adaptation are different than those required for coping and may require mobilizing additional outside resources or knowledge. For instance, ref. [15] reports that, to promote adaptive capacity, the community needs to engage in economic development, bolster social, political, and cultural capital, and improve information and communication capabilities.

- (iii) Transformative capacities refer to people's abilities to change the larger structures and systems in which they live, implying adaptation at larger scales and thus a more radical shift.

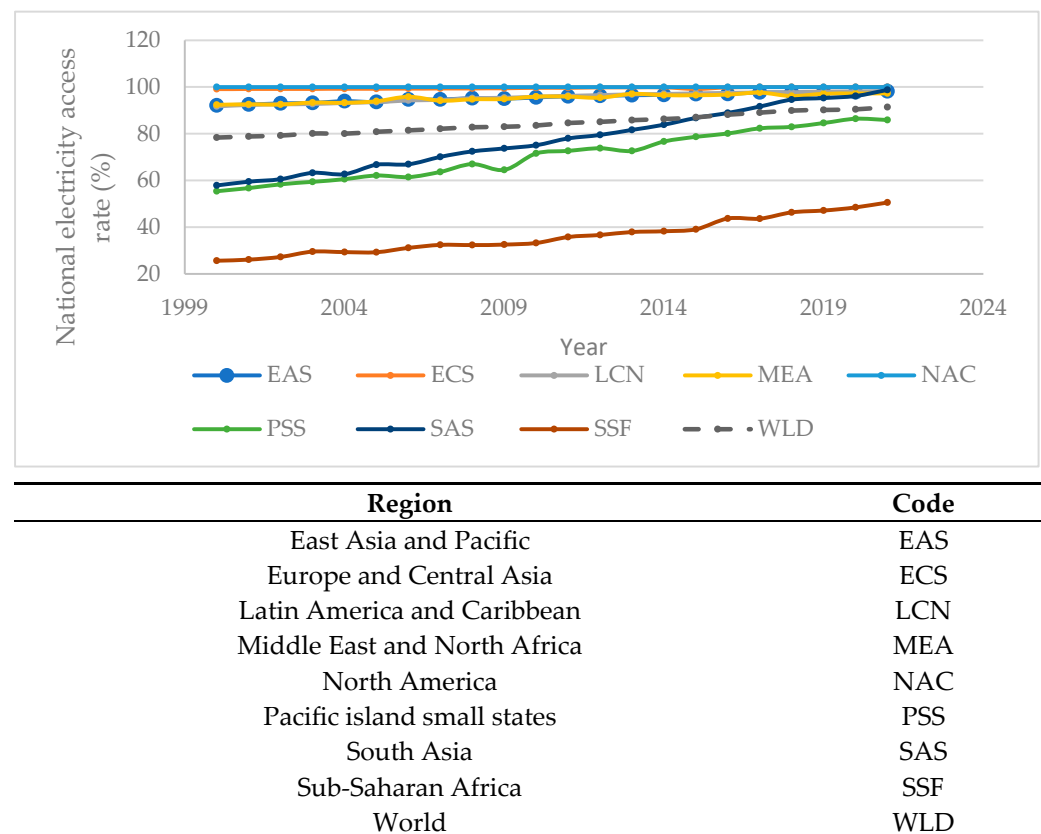


Figure 1. Electricity access in different regions around the world. Data source: [16].

Coping, adaptive, and transformative capacities are interconnected, mutually reinforcing, and exist across multiple levels, such as individual, household, community, district, national, and broader social–ecological systems [17]. Defining community resilience requires consideration of several aspects. For instance, community resilience should be discussed in the following contexts: (i) when the community is under significant threat, whether natural or human-induced; (ii) in relation to the specific vulnerabilities and threats the community faces; and (iii) with respect to the factors contributing to resilience, such as social, economic, cultural, natural, political, and human elements [18]. The next subsection provides an overview of this context in Fiji.

1.1. Making a Case for Resilience Study in Fiji's Context

As shown in Figure 2, Fiji is a small island developing state (SIDS) comprising over 300 islands, approximately one-third of which are permanently inhabited. The projected population in 2021 was 893,468, with a 2019 GDP of FJD 12,101.7 per capita [19]. According to the Multi-Indicator Cluster Survey Report, 85.7% of households nationwide have access to grid electricity supplied by Energy Fiji Limited, the sole power utility in Fiji. Additionally, 6.7% of households rely on off-grid electricity sources such as solar home systems,

diesel generators, solar–diesel–battery microgrids, or pico-hydro systems, while 7.7% of households lack any form of electricity [20]. Furthermore, 47.8% of households nationally do not use clean fuels or technologies for cooking [20]. Grid electricity is limited to the four main islands—Viti Levu, Vanua Levu, Taveuni, and Ovalau—with no interconnection between the islands. The remaining islands depend entirely on off-grid electricity systems.

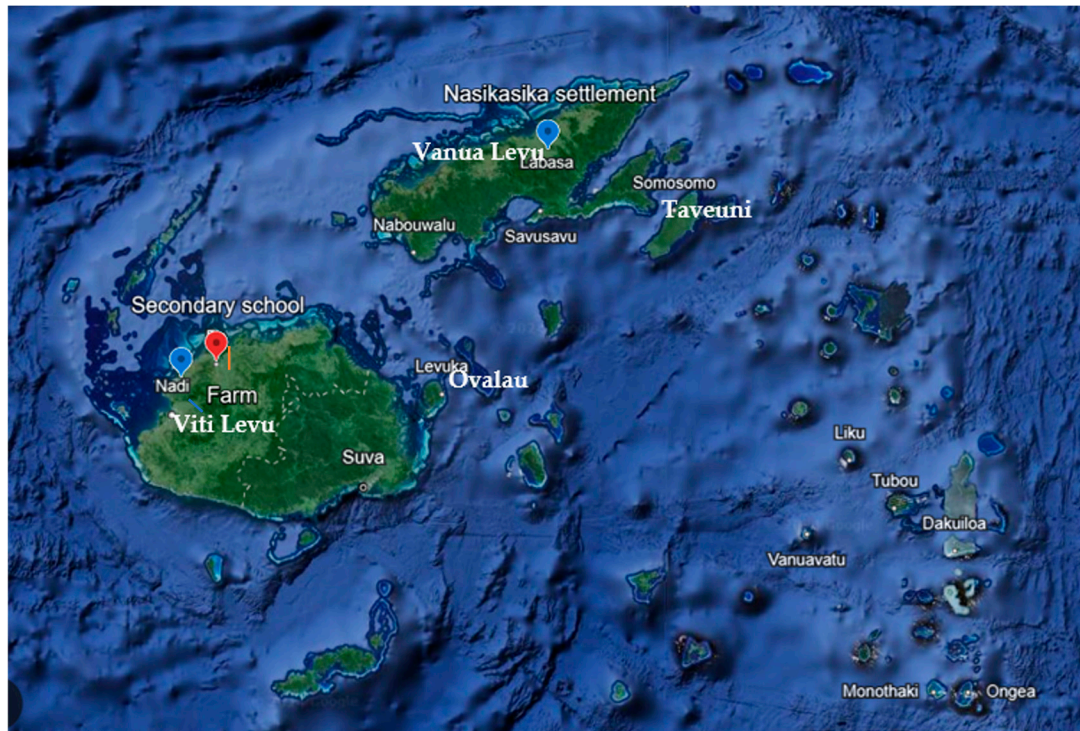


Figure 2. Map of Fiji showing all 3 sites of the case studies. Source: Map generated using Google Earth.

As a small island developing state (SIDS), Fiji is highly vulnerable to a range of shocks and stresses, particularly natural disasters, climatic events, and economic crises.

Natural Disasters:

(i) Tropical Cyclones:

Fiji has a long history of tropical cyclones, and while their annual frequency is expected to decrease, the intensity of these events is projected to increase [21]. For example, Tropical Cyclone Winston, a Category 5 cyclone, struck Fiji on February 20, 2016, causing FJD 1.42 billion in damage and claiming 44 lives [22]. Cyclones inflict widespread economic losses, impacting crops, livestock, forests, communications, housing, transport infrastructure, and power systems [23].

(ii) Floods and Droughts:

Climate variability in Fiji is primarily driven by El Niño and La Niña events. El Niño is associated with reduced rainfall and droughts, while La Niña typically brings excessive rainfall and flooding [23]. According to the Fiji Meteorological Service, 42 flooding events occurred between 2009 and 2022, averaging approximately three events annually [24]. Floods cause extensive damage, including to physical infrastructure such as bridges, homes, and buildings and crops, often resulting in hundreds of millions of dollars in losses [25]. They also lead to human casualties and the spread of waterborne diseases.

Droughts, often referred to as “creeping disasters” due to their gradual onset, cause severe water shortages in island nations like Fiji, despite their proximity to vast oceans.

These events disrupt food systems by depriving crops of necessary water, exacerbating food insecurity [26].

Climatic Events:

(i) Extreme Temperatures:

High average temperatures pose significant health risks to humans and have adverse effects on agriculture and livestock farming. Extreme heat can lead to crop failure, particularly in plants unable to tolerate high temperatures. Additionally, livestock species are vulnerable to heat stress, which negatively impacts their fertility in both males and females [27]. Households face increased energy demands for heating and cooling during such events, further straining resources.

(ii) Sea Level Rise:

Rising sea levels threaten the livelihoods of coastal communities, where approximately 75% of Fiji's population resides [28]. Saltwater intrusion into freshwater sources and land submersion have forced some highly vulnerable communities to relocate. While relocation may seem like a viable solution, it often results in profound emotional, mental, and cultural impacts. For iTaukei communities, relocation disrupts their deep ties to the land, which is symbolic of their ancestry and heritage [29].

Economic Crises:

(i) High Fuel and Food Prices:

Global recessions significantly affect fuel and food prices, which are further influenced by Fiji's political situation [30]. Rising prices result in inflation, eroding the purchasing power of individuals, particularly those from disadvantaged backgrounds [31].

(ii) Health Crisis:

The global COVID-19 pandemic severely impacted Fiji's economy and society [32]. According to ref. [33], the pandemic evolved from a health and economic crisis into a political crisis when the "no jab, no job" policy mandated by the government led to widespread job losses among unvaccinated individuals. Public protests ensued as people advocated for vaccination as a basic human right.

To address climate vulnerabilities, several adaptation strategies have been proposed for Fiji's four primary sectors: coastal resources, water resources, agriculture, and health. Policies and plans have been developed to promote sustainable resource management, including energy, as part of broader climate change adaptation efforts [34]. According to ref. [35], five major intervention areas have been identified to enhance climate resilience, with a key focus on strengthening infrastructure, including the energy sector, to support the needs of both people and the economy. However, energy is often perceived primarily as a mitigation strategy rather than an adaptation measure, underscoring the need for a more integrated approach.

1.2. Study Objectives

While energy is widely recognized as a climate change mitigation strategy and a means to enhance sustainable development [36], it should also be considered a crucial tool for climate change adaptation. As noted by ref. [37], research on community energy systems (CESs) is a relatively new field, with most studies focusing on developed countries. There is a significant gap in the literature on CESs in the context of Fiji, with the exception of ref. [38], who applied a local-level resilience framework to examine two types of solar photovoltaic (PV) systems (household-level and community-level) in off-grid communities and their role in building resilience.

This study aims to address this gap by analyzing how CESs contribute to building the resilience of communities in small island developing states (SIDSs), with a particular emphasis on Fiji. The study's objectives are to:

- (i) Identify and evaluate the various ways CESs strengthen community assets (including human, social, cultural, financial, natural, built, and political) across three distinct case studies in Fiji using a combination of qualitative and quantitative methods;
- (ii) Assess how these strengthened assets enhance communities' absorptive, adaptive, and transformative capacities in response to climate change impacts and other shocks; and
- (iii) Develop evidence-based recommendations for policymakers and practitioners to promote and implement CESs as a means to build community resilience in Fiji and other SIDSs based on insights from the case studies.

1.3. Innovation and Contribution

This study contributes to the limited literature on community energy systems (CESs) and resilience in small island developing states (SIDSs) by:

- (i) Expanding the Scope:

By examining three diverse case studies of CESs in Fiji, this study provides a comprehensive understanding of their potential. The first case study focuses on a grid-connected system at a school, where renewable energy technologies, such as rooftop solar PV and biogas systems, were installed. These systems function within the grid infrastructure and demonstrate key benefits, including enhanced energy stability, cost efficiency, and increased community collaboration toward energy resilience. The second case study explores an off-grid community that utilizes solar home systems, while the third examines a farm employing solar PV for irrigation. These off-grid technologies highlight solar PV's versatility in meeting diverse needs, including lighting homes, powering essential appliances, and supporting agricultural activities. They also demonstrate the capability of solar PV to serve remote areas where grid connectivity is either financially unfeasible or technically impractical due to geographical constraints. These findings highlight the limitations of traditional grid connections in providing universal energy access and underscore the importance of decentralized energy solutions.

- (ii) Applying a Resilience Framework:

This study employs a community resilience framework to analyze how CESs strengthen community assets—human, social, cultural, financial, natural, built, and political—and how these strengthened assets enhance communities' absorptive, adaptive, and transformative capacities in the face of challenges.

- (iii) Providing Policy Recommendations:

Drawing from the case studies, this research offers evidence-based policy recommendations to guide decision making and promote the adoption of CESs as a tool for building community resilience in Fiji and other SIDSs.

This research presents valuable insights into the multi-faceted benefits of CESs, moving beyond traditional focuses on energy access to emphasize their vital role in bolstering community resilience against various challenges. By examining how renewable energy (RE) initiatives drive sustainable development and resilience, this study reinforces the relevance of the community resilience framework proposed by [15].

The next section of the paper provides a thorough literature review, followed by Section 3, which outlines the methodology and steps undertaken in the research. Section 4 presents the results, and Section 5 discusses these findings, offering policy recommenda-

tions based on participant interviews, secondary data, and published literature. Finally, Section 6 concludes the study.

2. Literature Review

2.1. Terminology of Community Resilience and Frameworks

Renewable energy programs are often viewed as central to enhancing community resilience. The primary frameworks for understanding community resilience emerge from ecological, social, and economic perspectives [39]. From an ecological standpoint, resilience focuses on how interconnected community systems are, emphasizing the need for diversity and the capacity to adapt to challenges [40]. Social capital theory underscores the importance of social networks and relationships, suggesting that communities with strong social bonds are more capable of effectively responding to crises [38]. From an economic perspective, resilience refers to a community's ability to sustain its economic activities and recover from shocks through access to diverse resources [41].

Several key factors influence a community's resilience, particularly social connections, financial resources, and environmental factors. Social ties and active participation within communities are essential for resilience, as strong relationships enable communities to mobilize resources and respond to challenges [42]. Economic stability, underpinned by a variety of resources, supports resilience by helping communities adapt to disruptions [40]. Environmental factors, such as location and local conditions, shape resilience strategies. Communities situated in high-risk areas may need tailored approaches to address their specific vulnerabilities [38]. Successful case studies show that incorporating resilience measures into local government policies can make crisis management more effective [41].

Governance and policy play a vital role in fostering community resilience, as decisions made by local authorities influence how resources are allocated [42]. An inclusive decision-making process ensures that resilience efforts are more legitimate and effective [42]. Involving the community through participatory planning has been shown to improve resilience by enhancing people's sense of responsibility and investment in outcomes [40]. However, challenges such as limited resources, political barriers, and organizational obstacles can hinder the implementation of resilience strategies [41]. With climate change exacerbating vulnerabilities, exploring new technologies for data collection and communication is crucial for improving preparedness and response to disasters [38]. Future research should explore emerging trends in resilience practices, particularly within initiatives like the Renewable Energy (RE) Initiative, which aims to strengthen communities in the face of environmental challenges [42].

Resilience studies can be approached from two main angles: (i) energy infrastructure resilience and (ii) community energy resilience. Energy infrastructure resilience examines the ability of energy systems to withstand threats such as climate-related events and cyberattacks [43]. For example, to assess climate hazard impacts and enhance energy resilience in the design, planning, and operation of community-level energy systems, ref. [44] proposed a layered energy resilience framework that addresses engineering design, operations, and societal resilience. Similarly, ref. [45] found that the optimal design and operation, supported by a multi-stage resilient strategy, can significantly enhance the resilience of electricity and gas systems, ensuring sufficient reserve capacity and better fault recovery during outages. Additionally, [46] investigated the long-term sustainability of microgrids through resilience analysis.

Community energy resilience focuses on how energy infrastructure strengthens the resilience of the communities that depend on these systems [47]. Renewable energy projects foster resilience by: (i) improving energy efficiency and cost-effectiveness in the face of rising fuel prices, (ii) generating long-term revenue for communities, and (iii) fostering

stronger community ties around climate change issues [48]. A study in ref. [49] of three communities identified shared vision, social action, and community resilience as key dimensions contributing to sustainable energy initiatives. Renewable energy projects empower communities by increasing productivity and improving the environment [50]. Furthermore, such projects diversify energy sources, enhance collaboration, and build resilience [51].

The present study investigates “How do renewable energy initiatives contribute to the resilience of communities?” The following paragraphs discuss various frameworks used by researchers to assess community resilience.

A total of 36 resilience frameworks were identified by ref. [52], with the top eight dimensions most frequently cited in the literature: economic, social, human/health, physical, governance, environmental, food security, and poverty. Ref. [53] proposed a community energy resilience framework in which energy infrastructure—including technologies and networks—forms the backbone of an energy system. Energy resilience means preparing this infrastructure to withstand internal and external threats, which, in turn, strengthens community resilience by supporting the social networks and livelihoods dependent on the energy system. Governance integrates energy systems with the community, balancing exposure to risks, natural and built systems, users and managers of energy, and regulations [53]. Ref. [54] suggested the PEOPLES framework, which evaluates resilience across seven dimensions: Population and Demographics, Environmental/Ecosystem, Organized Governmental Services, Physical Infrastructure, Lifestyle and Community Competence, Economic Development, and Social–Cultural Capital.

Additionally, a review by ref. [55] found that the literature overwhelmingly supports the integration of sustainability and resilience indicators. Community resilience indicators (nine community-focused and eleven population-focused) were identified by refs. [56,57], which highlight that sustainability is a tri-dimensional concept—social, environmental, and economic—that can be applied to assess community development. A community’s livelihood is sustainable only if it can cope with and recover from shocks and stresses [10]. Therefore, if communities can sustain their livelihoods, they will build resilience. The Sustainable Livelihood Framework (SLF), described by ref. [58], bridges the gap between macro policies and micro-level realities, providing a methodology for resilience studies. The Community Capitals Framework (CCF) is another proposed method for understanding the processes underlying community development [59], identifying seven types of community capital (human, social, political, financial, natural, built, and cultural) that help measure the use and strength of community resources [60].

Natural capital forms the foundation of a community, including resources like land, air, water, and biodiversity, which ensure long-term sustainability and resilience [61].

Cultural capital represents the community’s soul, encompassing shared values, traditions, knowledge, and artistic expressions that strengthen social cohesion and promote cultural preservation [62].

Human capital serves as the engine of a community, representing individuals’ skills, knowledge, health, and education, which enhance a community’s ability to adapt to change and solve problems [63].

Social capital embodies the community’s bonds, networks, relationships, trust, and norms of reciprocity that facilitate communication, collaboration, and collective problem solving [64].

Political capital refers to the community’s voice, encompassing access to power, influence, and decision-making processes that enable advocacy for social change [65].

Financial capital provides the fuel for economic activity, including savings, income, access to credit, and investments, promoting economic self-sufficiency and reducing poverty [66].

Built capital involves the community's physical infrastructure, such as roads, buildings, utilities, communication networks, and public spaces, which support economic activity, social interactions, and access to services in a community [67].

By integrating the SLF and CCF, researchers can account for various actors within a community system, enabling a holistic assessment of factors like food security, environmental sustainability, and economic resilience [68]. Ref. [15] states that community resilience aims for a sustainable community with: (1) a healthy ecosystem, (2) a vibrant local economy, and (3) social equity and empowerment. A critical goal of this approach is to enhance and maintain the seven types of capital outlined in both the SLF and CCF.

2.2. Studies on Community Resilience from the RE Initiative

While renewable energy systems primarily aim to reduce greenhouse gas emissions, they also play a significant role in enhancing climate resilience. These systems can prevent disruptions caused by natural disasters and enable quicker restoration of power, a critical advantage over backup diesel and gas generators, which often fail during prolonged outages due to fuel shortages and aging infrastructure [47,69]. Solar energy systems, particularly decentralized options such as rooftop photovoltaics, boost energy security, efficiency, and resilience by reducing dependence on external supply. These systems are reliable under optimal weather conditions and with proper battery storage [70]. Despite their potential, the role of energy resilience at the municipal level remains underexplored, even though studies emphasize the contribution of rooftop solar and management algorithms to improving resilience.

Utility-scale solar photovoltaic (PV) systems present a clean energy solution to support countries transitioning to low-carbon development, meeting both national and international environmental targets. A feasibility study conducted using RETScreen for a 211.75 MW grid-connected solar PV system in Cameroon confirms its economic and environmental viability, urging its implementation to further the country's renewable energy goals [71]. Additional studies [72,73] confirm that, given available resources, solar PV can provide substantial benefits for nations.

Renewable energy systems are also crucial in providing resilient and sustainable energy for rural, remote, and island communities. A study of a solar PV mini-grid in Ghana revealed that despite the availability of solar resources, factors such as inadequate battery storage, distribution losses, and limited daylight-based economic activity hinder their full utilization [74]. To address these issues, the authors of ref. [74] suggest enhancing system resilience by integrating alternative energy sources, minimizing redundancy, and addressing climate risks within mini-grid operations. This aligns with other recommendations [75], which propose that island communities can boost self-resilience by minimizing energy exchange with the mainland and adopting electrification technologies like heat pumps, hydrogen production, and electric vehicles. Similarly, RETScreen analysis demonstrates how integrating solar and wind energy systems with storage solutions such as thermal and compressed air systems can make residential communities carbon-neutral while ensuring energy sustainability [76]. Further research in Greece using RETScreen and Energy Plan tools explored creating positive energy communities through retrofitting and renewable technologies, demonstrating substantial CO₂ reductions and energy savings that align with EU net-zero goals for 2050 [77].

Solar PV systems are also gaining traction in agricultural sectors. Studies on the integration of photovoltaic systems in greenhouse operations, such as Zina Fresh in Nige-

ria, confirm their techno-economic viability using RETScreen Expert, showing annual outputs of 430 MWh, a 6.7-year payback period, and significant CO₂ reduction [78]. Additional research on sustainable greenhouse agriculture in Nigeria and microgrid configurations in Palestine further demonstrates the potential for renewable energy in enhancing resilience by addressing energy and water scarcity in remote agricultural communities [79,80]. Agrivoltaics—systems combining solar energy generation with agricultural production—represent a promising solution to address resource scarcity and promote sustainable practices that benefit both the environment and society [81].

Community-based distributed energy systems, including solar, wind, and microhydro, empower local populations, improve livelihoods, and enhance overall resilience. A combined conceptual framework for distributed renewable-energy-based infrastructure shows its contribution to building community resilience [82]. Moreover, an MILP-based model optimizing energy consumption in solar home systems offers improved access to energy and climate adaptation benefits, particularly for women-headed households in off-grid environments [83]. Research [84] on the value of rooftop solar systems further underscores their potential to increase community resilience, particularly during natural disasters.

2.3. Enhancing Community Resilience Through RE Initiatives in the Pacific

The Pacific region has outlined a framework for resilient development through the Pacific 2017–2030 document, which aims to promote low-carbon development. By minimizing carbon emissions and maximizing carbon uptake (e.g., through reforestation), island countries enhance both energy security and natural capital [85]. Additionally, the Framework for Energy Security and Resilience in the Pacific (2021–2030) emphasizes the importance of improving energy sector robustness to withstand climate change and natural disasters, while ensuring universal energy access through enhanced efficiency measures [86].

A conceptual model designed to assess vulnerability and resilience in coastal communities in Fiji highlights the importance of community engagement and local knowledge for developing effective climate change adaptation strategies [87]. However, this model did not examine the role of energy systems in enhancing community resilience. In Fiji, a study of a solar PV system on Viwa Island highlighted the critical role of community involvement, thorough technology assessment, and continuous monitoring for achieving sustainable outcomes [88]. Research by [41] stresses that addressing climate change and other challenges requires innovation in energy planning, community engagement, and decentralized energy systems to build resilience in Pacific Island countries and territories. Accordingly, this study focuses on decentralized energy systems and their contribution to enhancing community resilience.

3. Materials and Methods

This study employed a mixed-method approach to explore the relationship between energy systems and community resilience in Fiji. The qualitative aspect utilized the energy biographies method, inspired by [49], to investigate how people's experiences with energy systems shape their livelihoods and communities. This involved in-depth case studies to provide a comprehensive understanding of these dynamics. To supplement the findings, the study incorporated a quantitative approach using the RETScreen Expert tool (developed by the Government of Canada). This globally recognized clean energy management software assesses the technical, financial, and environmental aspects of renewable energy (RE) projects [89]. RETScreen facilitates advanced analyses of costs, financial risks, and emissions while maintaining accuracy with its optimized algorithms and robust database, outperforming similar tools like HOMER (originally developed by the National Renewable Energy Laboratory (NREL) but now enhanced and distributed by UL Solutions) and PVSyst

(developed in Switzerland by André Mermoud), [89,90]. Section 2.2 previously discussed various studies employing RETScreen to evaluate the sustainability and resilience of solar PV systems.

3.1. Qualitative Method

(i) Data Collection Instruments

To gather qualitative data, third-year university physics students were assigned research tasks on how specific renewable energy systems affect community livelihoods. Three exemplary assignments were incorporated into this study. The primary data collection method was semi-structured interviews, guided by a detailed interview framework adapted from [91]. Topics covered included:

- Demographics: Age, gender, occupation, education level, and household size.
- Socioeconomic factors: Income, employment opportunities, and access to essential services.
- Energy context: Current energy sources, challenges, perceptions of renewable energy, and adaptive strategies employed by communities to address climate change and disasters.

(ii) Site Selection

Three diverse communities were chosen as case studies based on criteria such as completeness of received data, variations in energy access, diversity of renewable energy technologies in use, and the potential to provide rich insights into community resilience. The sites are as follows:

- Secondary School in Ba (Figure 3a)

Location: Latitude -17.5° and longitude 177.7° (Figure 2, red pin).

History: Established in 1970, the school has 670 students, 51 teachers, and offers 40 subjects across well-equipped facilities, including science labs, computer labs, industrial arts workshops, and an air-conditioned library and staff room.

Current Energy Systems: Electricity is sourced from the national grid (Energy Fiji Limited) and a grid-connected solar PV system. Previously reliant on grid electricity alone, the school also had a 1.2 kW diesel generator, which has been non-operational for some time. Water supply includes a utility connection from the Water Authority of Fiji (WAF), a borehole pumping spring water to storage tanks, and rainwater-harvesting systems.

Renewable Energy Initiatives (Figure 4):

- Solar PV System: A 25 kW grid-connected solar system installed in July 2023, funded by the USD 100,000 Zayed Sustainability Prize [92].
- Rainwater-Harvesting System: Three 3200-liter tanks were installed alongside the solar PV system to enhance water resilience.
- Biogas Energy System: Installed in October 2020 and donated by the Fiji Water Foundation, it provides approximately one hour of cooking gas every two days.

These initiatives collectively demonstrate the school's commitment to sustainability and serve as practical examples of renewable energy adoption enhancing community resilience.

- Rural community in Nasikasika, Labasa (Figure 3b)

This settlement comprises six households powered by solar home systems (SHSs), located at approximately latitude -16.5° and longitude 179.4° (Figure 2, blue pin on Vanua Levu). The Nasikasika settlement comprises six households with a total of 31 residents, including 14 adults and 17 children under the age of 19. The families are primarily engaged in vegetable and sugarcane farming, and the settlement spans an area of approximately 100 acres. Electricity is supplied through 300 W solar home systems (SHSs), while water is provided via a utility water supply.



Figure 3. Photos of the sites in the case study. Photos supplied by interviewees.



Figure 4. RE initiatives in the secondary school. Photos provided by the school.

Each household is equipped with two 300 W solar photovoltaic (PV) panels mounted on monopoles outside the homes, with the control system installed indoors, as depicted in Figure 5. These SHSs were provided by the Fiji Sugar Corporation (FSC) as part of an initiative to support sugarcane farmers in the Nakoroutari area, including the six households in Nasikasika. The cost of each SHS is approximately FJD 8,000, amounting to a total investment of FJD 48,000 for the settlement. Installation of the systems was completed in April 2017 by an energy service company, with FSC covering the costs.

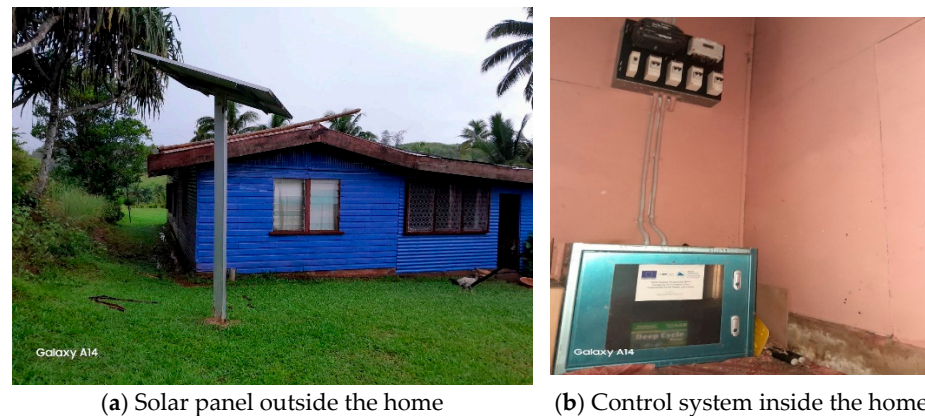


Figure 5. A solar home system in Nasikasika settlement. Photos provided by interviewee.

Additionally, each household owns a 650 VA Yamaha premix generator, which had been in use before the installation of the solar PV systems.

- Farming Household in Buabua, Lautoka (Figure 3c)

This household leverages a solar PV system for farm irrigation and powering a flat occupied by farmworkers. Located at a latitude of -17.6° and longitude of 177.5° (Figure 2, blue pin on Viti Levu), the farm spans 10 acres and is managed by a family of three: a 49-year-old father with a primary school education, a 47-year-old mother with secondary school education, and their 25-year-old son, who holds a Trade Diploma in Electrical and Electronics Engineering.

The solar PV system, installed in July 2021 at a cost of approximately FJD 15,000, was financed and designed by the son, with assistance from his father during installation. The system powers a 1 hp water pump for sprinkler irrigation and supplies electricity to a newly constructed flat on the property, housing three farmworkers. The flat's total energy demand, ranging from 3–4 kW, covers basic appliances such as five lights, a small radio, TV, iron, electric heater, and rice cooker. The flat's energy needs are fully met by solar power, eliminating electricity costs.

(iii) Data Collection Procedures

Students were briefed on the assignment's aim, interview protocols, and data collection methods. Study sites were selected based on their convenience to the students and the presence of renewable energy initiatives. Prior to data collection, students sought methodological guidance from the course lecturer and participants were provided with a letter outlining the assignment's objectives, assuring their participation was voluntary and could be withdrawn at any time. Interviews and data collection occurred only after obtaining participant consent, primarily consulting household or community heads. Responses were recorded manually, and additional information was gathered through local media reports. Follow-up questions were addressed during the preparation of this paper to clarify and fill gaps in the data.

(iv) Data Analysis

The analysis employed the Community Resilience Framework (CRF) proposed by [15] to evaluate how renewable energy initiatives impact community resilience by building absorptive, adaptive, and transformative capacities. Data were thematically analyzed based on the seven community capitals outlined in the CRF (shown in Figure 6), demonstrating how the initiatives strengthened these capitals and contributed to resilience against shocks and stresses. Findings were contextualized within broader literature on energy, sustain-

ability, and community development. To minimize bias, the RETScreen tool was used to validate energy output, emissions reductions, and cost savings.

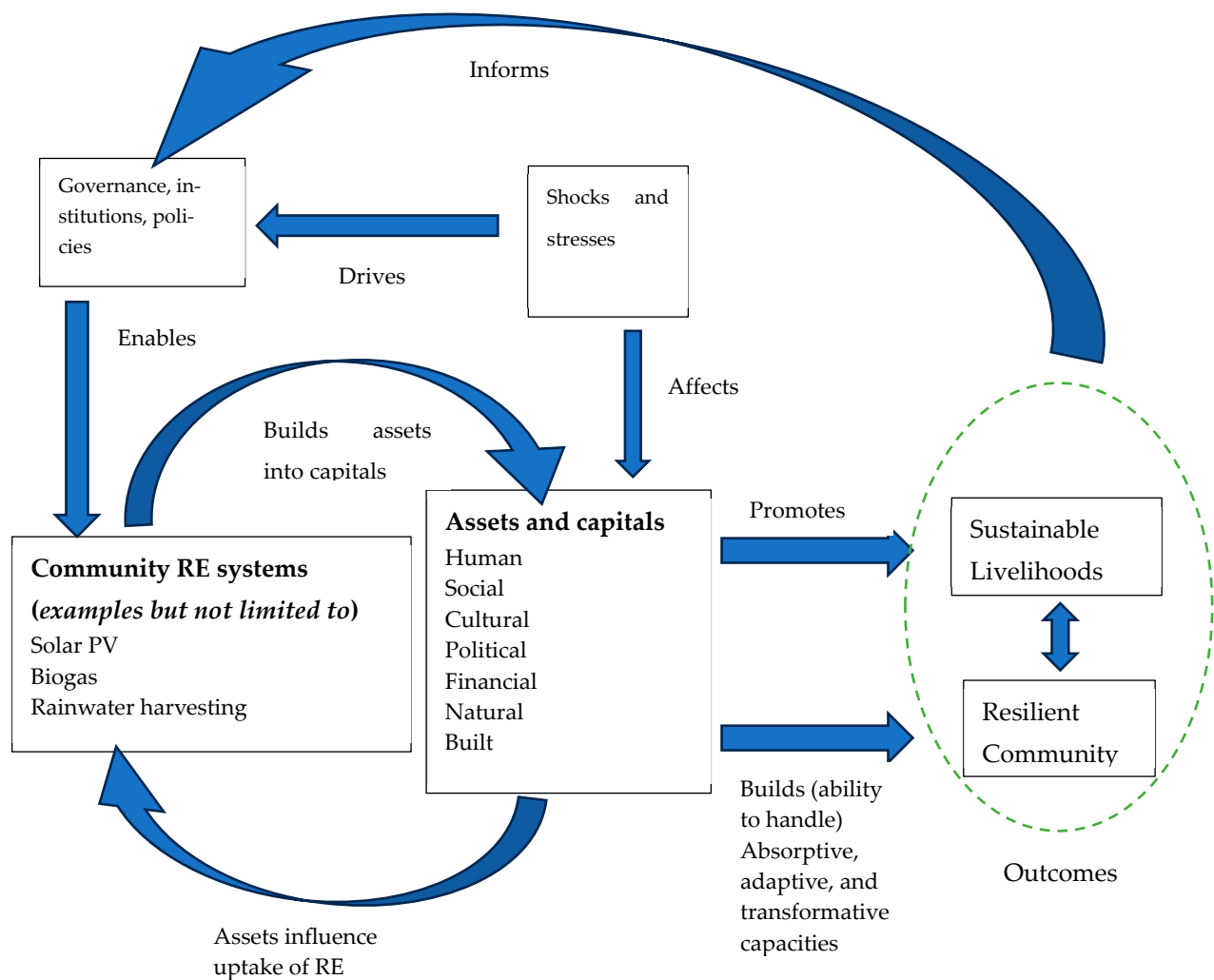


Figure 6. Framework used to assess community resilience. Adapted from [10,15,58].

3.2. Quantitative Method

The RETScreen tool was utilized to evaluate the energy output, greenhouse gas (GHG) emission reductions, and cost savings for the three case studies. These parameters were used to compare the perceived benefits reported by interviewees and to validate the qualitative findings. RETScreen is highly accurate for feasibility analyses of renewable energy systems. When compared with the System Advisor Model (SAM) developed by the National Renewable Energy Laboratory, the percentage error in analysis is less than 1.20%, highlighting the reliability and precision of the simulation results, thus affirming the feasibility assessments of the photovoltaic (PV) systems [93].

The input parameters for the case studies are detailed in Table 1, and the systems' schematic diagrams are presented in Figure 7. The grid-connected secondary school system, modeled without a battery backup (Figure 7a), reflects actual operational conditions, where only partial load is supplied during power disruptions. The analysis focused on determining electricity generation, GHG emissions reduced, and the financial benefits of the project.

Table 1. Input parameters for case studies.

25 kW Grid-Connected Solar PV at Secondary School		0.3 kW SHS at a Rural Settlement (for One Home)		4.2 kW Off-Grid Solar PV System at a Farm	
Parameters	Value	Parameters	Value	Parameters	Value
Electricity export rate (USD/kWh)	0.085	Electricity export rate (USD/kWh)	0.17	Electricity export rate (USD/kWh)	0.17
Fuel (USD/L)	-	Fuel (USD/L)	1.50	Fuel (USD/L)	1.50
Solar PV		Load characteristics		Load characteristics	
Type	Mono-silicon	Daily AC load (kWh)	Base case and proposed case: 0.6371	Daily AC load (kWh)	Base case: 4.0 Proposed case: 8.4
Power capacity (kW)	25.16	Annual peak load (kW)	0.13	Annual peak load (kW)	4.0
Number of panels	136	Inverter for SHS		Inverter	
Efficiency (%)	14.8	Capacity (kW)	0.3	Capacity (kW)	4.0
Inverter		Efficiency (%)	80	Efficiency (%)	90
Capacity (kW)	25	Battery for SHS		Battery	
Efficiency (%)	90	Days of autonomy	4	Days of autonomy	4
Financials		Voltage	12	Voltage	48
Cost (USD/kW)	1500	Efficiency (%)	85	Efficiency (%)	85
O&M cost (USD/kW/year)	39	Max depth of discharge (%)	80	Max depth of discharge (%)	80
Inflation rate (%)	3	Charge controller efficiency (%)	95	Charge controller efficiency (%)	95
Discount rate (%)	10	Capacity (Ah)	200	Capacity (Ah)	1101
Project life (years)	25	Solar PV		Solar PV	
Grid emission factor (tCO ₂ /MWh)	0.320	Tracking mode	Fixed	Tracking mode	Fixed
		Slope	18	Slope	18
		Type	Mono-silicon	Type	Mono-silicon
		Power capacity (kW)	0.33	Power capacity (kW)	4.185
		Number of panels	2	Number of panels	9
		Efficiency (%)	13.2	Efficiency (%)	21.1
		Initial costs (USD/kW)	4000	Initial costs (USD/kW)	7500
		O&M costs (USD/kW/year)	30	O&M costs (USD/kW/yr)	30
		Financial		Financials	
		Inflation rate (%)	3	Inflation rate (%)	3
		Discount rate (%)	10	Discount rate (%)	10
		Project life (years)	25	Project life (years)	25

For the solar home systems, one representative household was modeled (Figure 7b), and the results were extrapolated to all six households to estimate the community-wide benefits. Similarly, the solar PV system installed at the Buabua farm was analyzed for its dual purpose—powering a flat and operating a 1 hp water pump used for sprinkler irrigation three hours daily (Table 1). Figure 7c illustrates the system setup, including the flat’s electrical load, which was incorporated after the PV system installation. These models provide a comprehensive assessment of the renewable energy initiatives’ technical and economic impacts, reinforcing the qualitative insights gathered through interviews.

According to Table 1, the electricity export rate for the school is set at USD 0.085/kWh, which corresponds to the subsidized tariff charged to the school by the electric utility company. This subsidy is supplemented by the government, which pays an additional USD 0.085/kWh for the electricity consumed. For the solar home systems (SHSs) and the water pump on the farm, the fuel rate is set at USD 1.50/L, reflecting the current retail price for diesel and gasoline [94].

The cost of the grid-connected solar PV system for the school is assumed to be USD 1500/kW, the conventional rate for similar installations in Fiji [95]. The costs for the SHS and the farm’s solar PV system were derived from data shared by interviewees during the data collection phase. Financial analysis parameters, including an inflation rate of 3% and a discount rate of 10%, were aligned with previous studies [96,97].

For the off-grid systems, the daily AC load was calculated as 0.6371 kWh for the SHS. At the farm, the base-case daily load was taken as 4 kWh (representing the water pump only), whereas the proposed case has an increased load of 8.4 kWh, reflecting the additional energy demand from powering a flat with the solar PV system.

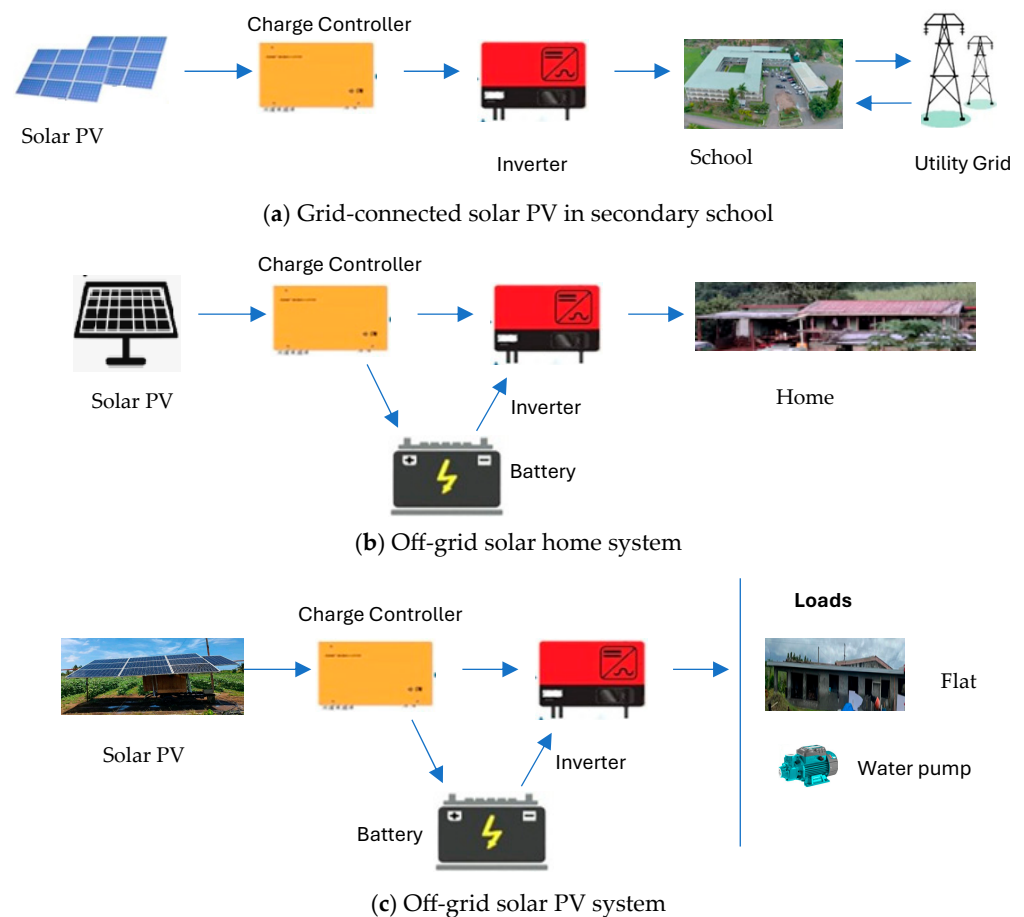


Figure 7. Schematic diagrams for solar PV systems in case studies.

Daily solar radiation and precipitation data for the sites, shown in Figure 8, were obtained from RETScreen, which uses NASA climate data. Due to their proximity, the farm and school share the same weather data. Notably, the average annual precipitation at the Nasikasika settlement is higher (1957.41 mm) compared to the other two locations (1725.32 mm). Similarly, Nasikasika also receives higher average daily horizontal solar radiation (5.135 kWh/m²/day) than the other sites (4.99 kWh/m²/day).

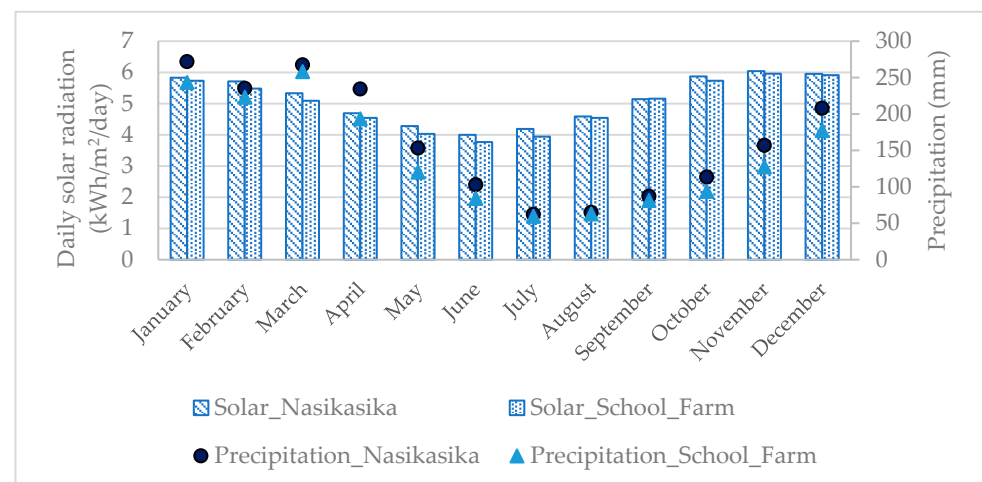


Figure 8. Climate data for the chosen sites.

4. Results

4.1. Impact of RE Systems on the School

The findings from the interviews were analyzed using the framework illustrated in Figure 6. The information gathered during the data collection phase was translated into narrative form. The subsections below discuss how renewable energy (RE) initiatives in the three case studies have influenced the seven capitals: human, social, cultural, political, financial, natural, and built.

4.1.1. RE System's Impact on the School

Human Capital:

The RE initiatives at the school have fostered a spirit of environmental consciousness among students, staff, and the community. Regular teacher training sessions and workshops are held during meetings, where the teacher in charge and the head of the school discuss the implementation and functioning of new systems (e.g., solar PV, biogas, rainwater harvesting). Students are actively involved in these systems, such as feeding biogas digesters, observing gas production, and learning about solar PV electricity generation. These initiatives serve as living labs, offering experiential learning for both students and the broader school community. Furthermore, the school management is equipped to handle minor operational faults in the solar PV system, knowing how to switch to grid electricity and contact the energy service company (ESCO) when necessary.

Social Capital:

The introduction of solar PV, biogas digesters, and rainwater-harvesting systems has strengthened collaborations among teachers, students, school administrators, the private sector, and government entities. For instance, students contributed by creating videos about renewable energy for the Zayed Sustainability Program, promoting teamwork and raising awareness. Beyond agricultural students, students of other disciplines engage in farming activities, exemplifying interdisciplinary collaboration. Students eagerly participated in setting up the biogas digester and shared their experiences with peers. Additionally, some teachers have reached out to other schools to increase awareness of renewable energy systems. This shared commitment has cultivated a sense of pride and unity within the school and the community, encouraging others to adopt sustainable practices.

Cultural Capital:

The renewable energy initiatives have led to greater community awareness in the Ba region. Students share their knowledge of these systems with their families and neighbors, inspiring more widespread adoption of similar technologies. This exchange not only promotes cultural sustainability but also reinforces the school's role as a community leader in renewable energy practices.

Political Capital:

As a community-owned institution, the school has established strong connections with local people, the Ministry of Education, and other government and non-governmental bodies. These relationships were instrumental in securing support from the Ministry of Education, the Ministry of Works, Meteorological Services, and funding agencies such as Zayed Sustainability during the planning and implementation phases. The school's participation in the Zayed Sustainability competition was sparked by a teacher's awareness of the opportunity, coupled with the head of school's support. Winning the prize ultimately enabled the implementation of the RE projects.

Financial Capital:

Adopting renewable energy sources such as solar PV and biogas has significantly reduced the school's reliance on costly fossil fuels. From May 2023 to April 2024, the school saved approximately FJD 240 (USD 120) monthly on electricity, as shown in Figure 9.

Although electricity export data are missing for May 2019–December 2022 due to record-keeping issues, a simulation using the RETScreen tool (Table 2) estimates annual savings of USD 2,903 (approximately USD 242 per month). The difference arises because the school is not yet exporting surplus electricity to the grid, which could further increase savings. Additionally, the school saves FJD 200 (USD 100) annually on LPG costs for cooking by using a biogas stove. According to the head of the school, the savings are allocated to improving teaching and learning activities, such as upgrading technological infrastructure and installing smart boards in classrooms.

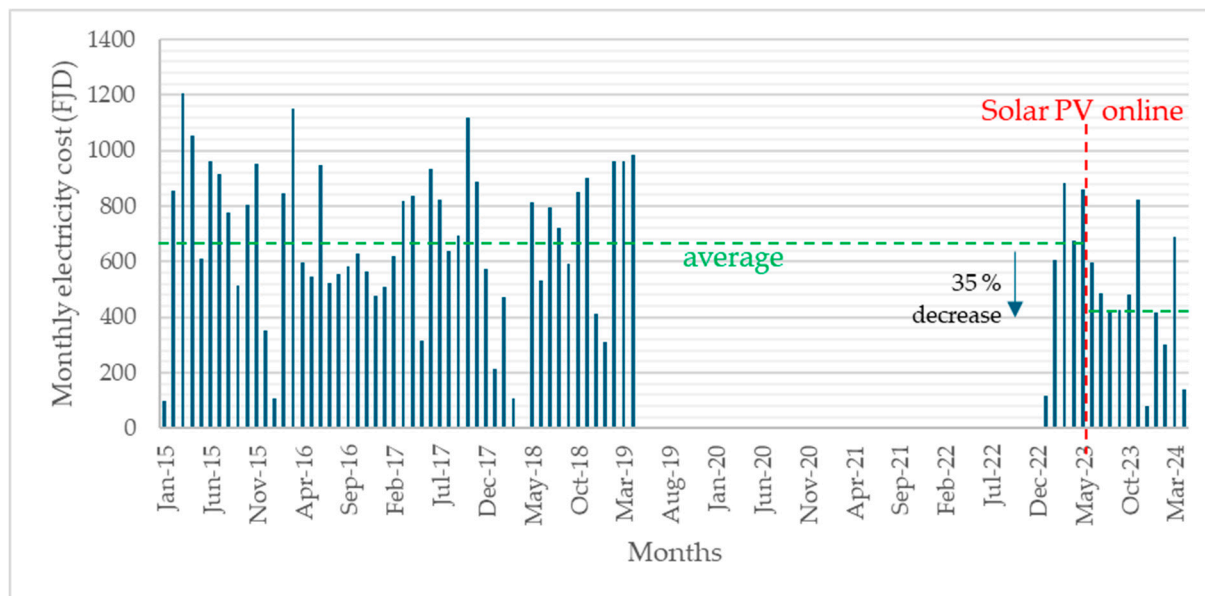


Figure 9. Electricity bill for the secondary school. Data source: School records.

Table 2. RETScreen outputs.

	25 kW Solar PV in Secondary School	0.3 kW Solar Home System at Settlement (One Home)	4.2 kW Off-Grid Solar PV at the Farm
Parameter	Values	Values	Values
Annual energy output (kWh)	34,159	232	3046
Gross annual emissions savings (tCO ₂)	10.9	0.59	10.7
Annual savings (USD)	2903	430	1170
No Grant	-	-	-
Simple payback (years)	19.6	7.4	7.2
Equity payback (years)	>Project lifetime	6.7	6.7
Net present value (USD)	−23,033	3232	3668
Annual life cycle savings (USD/year)	−2538	356	404
Benefit–cost ratio	0.39	1.5	1.5
GHG reduction cost (USD/tCO ₂)	232	−602	−210
Energy production cost (USD/kWh)	0.159	2.93	0.323
With Grant (USD)	75,000	4000	8000
Simple payback (years)	Immediate	2.5	Immediate
Equity payback (years)	Immediate	2.4	Immediate
Net present value (USD)	51,967	7232	11,668
Annual life cycle savings (USD/year)	5725	797	1285
Benefit–cost ratio	2.4	2.2	2.6
GHG reduction cost (USD/tCO ₂)	−524	−1347	−669
Energy production cost (USD/kWh)	0.00	1.03	0.036

Natural Capital

The school's natural capital has been significantly enhanced by implementing renewable energy (RE) initiatives. Solar panels installed on the rooftops generate clean electricity, reducing the school's reliance on fossil fuels and contributing to lower carbon emissions. Based on RETScreen analysis, the school's grid-connected solar PV system, with Fiji's grid emission factor of 0.320 tCO₂/MWh, has the potential to prevent 10.9 tons of CO₂ emissions annually. Additionally, the biogas system has replaced the need for chemical fertilizers. The liquid slurry produced by the biogas system serves as an organic fertilizer for the school's agricultural activities, promoting sustainable and eco-friendly farming practices. Overall, these RE initiatives contribute to the preservation of natural resources while mitigating climate change impacts.

Built Capital

The school's physical infrastructure has improved considerably due to the RE projects. Solar panels installed on unused spaces, such as 124 m² of rooftop area, have turned underutilized zones into energy-producing assets. Other physical infrastructure improvements include a biogas digester with a stove and water tanks, which collectively enhance the school's built capital. These investments not only align with the school's commitment to sustainability but also strengthen its resilience to climate change and other potential disruptions. The transition to renewable energy underscores a move toward a sustainable and disaster-resilient campus.

4.1.2. Solar PV's Impact on the Community

Human Capital:

The introduction of solar power in households has enhanced human capital by raising awareness among community members, particularly the younger generation. The availability of reliable lighting has improved children's ability to study, replacing inefficient and hazardous kerosene lamps. The installation of solar home systems (SHSs) has also provided residents with hands-on experience, enabling them to acquire skills in installing and maintaining solar panels, wiring, and system integration. Interviewees reported learning to handle technical aspects like installation and maintenance independently.

Despite their limited capacity, solar home systems have educated users about energy consumption management, teaching them to avoid overloading their systems. For heavier electrical loads, such as ironing and operating power tools, a premix generator is used. This awareness has resulted in smooth operation without significant issues since 2017. Solar home systems have also enhanced households' quality of life, providing access to television for news, sports (e.g., rugby), and entertainment.

Social Capital:

Solar home systems have fostered social cohesion within the community by enabling night functions and other gatherings powered by solar electricity. As seen in Figure 10, events can now be held after dark, enhancing community interactions. Community members also share their experiences and successes with neighboring settlements, encouraging broader adoption of similar technologies. Access to mobile phones powered by solar energy ensures connectivity among families and enables children to conduct school research, further enriching social networks and educational opportunities.

These advancements collectively demonstrate the tangible benefits of renewable energy projects, strengthening not only individual households but also the broader community.



Figure 10. Prayer session using solar electricity for light at Nasikasika settlement. Photo supplied by the interviewee.

Cultural Capital

The introduction of solar electricity has transformed cultural practices within the community. For example, religious scripture readings, such as those of the Ramayan Mandali, can now be performed at night, enhancing community engagement in spiritual activities. Additionally, households actively share their success stories about solar energy during these gatherings, fostering awareness of sustainable energy practices and inspiring others to adopt similar solutions.

Political Capital

Political capital has played a key role in driving renewable energy adoption in the Nasikasika settlement. Given the area's strong connection to sugarcane farming, a field officer from the Fiji Sugar Corporation (FSC) facilitated the collection and submission of household data to FSC, leading to the installation of solar home systems. This collaborative effort highlights the value of leveraging local networks and institutional support for sustainable development.

Financial Capital

The financial benefits of solar photovoltaic (PV) systems in this settlement are considerable. With the FSC providing the solar systems as a grant, households saved approximately FJD 8000 (USD 4000) on procurement and installation costs. Furthermore, households now enjoy free electricity, unlike communities reliant on grid power, which costs FJD 0.34 per kWh.

Before the installation of solar PV systems, households spent FJD 400–500 annually on generator fuel. Now, fuel costs have dropped to around FJD 80 annually. Households also save an additional FJD 20 per week by reducing their use of kerosene lamps, which are no longer necessary due to the availability of solar-generated electricity.

According to RETScreen analysis (see Table 2), each household saves approximately USD 430 per year by using solar home systems instead of a 0.65 kW diesel generator. These cumulative savings provide financial security for emergencies, particularly vital for the farming community, which lacks fixed incomes.

Natural Capital

Solar home systems (SHSs) enhance natural capital by reducing greenhouse gas (GHG) emissions. By displacing kerosene lamps and significantly reducing reliance on diesel generators, households cut down on both CO₂ emissions and black carbon. Based on Table 2, each household reduces emissions by approximately 0.59 tCO₂ annually, translating to a total savings of 3.54 tCO₂ per year for the entire settlement. This transition contributes to a cleaner environment and promotes the sustainable use of natural resources.

Built Capital

The installation of solar PV systems has significantly improved built capital in the settlement. The solar installations have increased household asset valuation, making the properties more attractive for potential future sales. The physical convenience brought by solar-powered amenities, such as electric irons and solar freezers, has also greatly improved household efficiency and quality of life.

Respondents reported that switching from charcoal irons to electric irons has eliminated delays caused by charcoal shortages. Additionally, the recent acquisition of a solar-powered freezer by one of the households enables families to store perishable foods longer, reducing the frequency of market trips and ensuring safer food storage. This advancement contributes to financial savings and enhances food security.

4.1.3. Solar PV's Impact on Farm and Household

Human Capital

The son's diploma qualification and engineering knowledge served as the foundation for installing solar PV on the family farm. Referred to as the "initiator", his expertise and vision were key drivers behind this project, underscoring the importance of educated leaders in advancing renewable energy [98]. Replacing the gasoline-powered water pump with a solar-powered alternative has improved both productivity and health by eliminating air pollution.

Social Capital

The son's decision to implement solar PV on the farm has sparked community interest in the Buabua area, prompting neighbors to inquire about installation costs, technical specifications, and the system's durability. By sharing his experience, the family has contributed to broader social awareness and inspired others to consider solar energy for their own needs.

Cultural Capital

The family's involvement in the "Buabua Ramayan Mandali" reflects their active engagement in cultural and religious activities. These gatherings offer opportunities to discuss their renewable energy ventures, reinforcing the positive impact of solar energy on their lives and motivating others to follow suit.

Political Capital

The son's leadership in advancing sustainable agriculture exemplifies the alignment of personal initiative and political capital. His engineering education and internet access allowed him to research and design the system independently. By leveraging his connections and knowledge, the family acquired a robust system that supports their vision for sustainable farming practices. This integration of education, technology, and policy demonstrates a pathway to transforming rural communities.

Financial Capital

The transition to solar power has delivered substantial financial benefits. The family has reduced fuel costs for the water pump by 95%, saving approximately FJD 1500–2000 annually. RETScreen analysis confirms annual savings of USD 1170 from solar-powered irrigation and electricity for worker accommodations.

In addition, the family benefits indirectly from high farm yields, which reduce dependence on market purchases for vegetables, further buffering them from fluctuating fuel and food prices. The son's renewable energy business, employing five people, adds to the household income while contributing to local economic development.

Natural Capital

The carbon footprint of the farm has been significantly reduced through the adoption of solar PV for irrigation and household electricity. The renewable energy-powered sprinkler

systems ensure environmentally friendly irrigation, supporting healthy crop yields without the ecological costs of gasoline dependency.

Built Capital

The family's portfolio of assets, including farmland, houses, and vehicles, has been diversified and enhanced by solar PV. The integration of solar systems on the farm and in the home illustrates their commitment to resilience and sustainability, laying the groundwork for long-term growth and energy security.

4.2. Quantitative Findings

The energy output, GHG emissions reduction, and cost savings mentioned by interviewees are complemented by the quantitative results shown in Table 2. The annual energy output for the secondary school is 34,159 kWh from the 25 kW grid-connected solar PV system, which leads to a reduction of 10.9 tCO₂ per annum in GHG emissions and USD 2903 in electricity bill savings. For one SHS, the annual energy output is 232 kWh, resulting in a reduction of 0.59 tCO₂ per annum and USD 430 in fuel cost savings. For the off-grid solar PV at the farm, the annual energy output is 3046 kWh, which reduces 10.7 tCO₂ per annum and saves USD 1170 in fuel costs.

To assess the financial viability, the RETScreen analysis was conducted for two scenarios: one with no grant provided and another with a grant for the renewable energy (RE) initiative. For the solar home system (SHS) and the grid-connected solar photovoltaic (PV) system at the secondary school, the projects were fully funded by donors. However, for the off-grid solar PV system at the farm, the investment was made by the family without any financial aid.

As shown in Table 2, if the school had not received funding, the project would not have been financially viable, leading to a negative net present value (NPV) and a benefit-to-cost ratio (BCR) of less than 1. A negative NPV indicates that the project is not profitable, and a BCR of less than 1 means that the costs outweigh the benefits of the project [96,97].

With the solar PV project at the school fully funded, RETScreen analysis shows that there is no energy production cost, and the NPV of the project is almost USD 52,000. This surplus could be used by the secondary school to enhance their learning and teaching resources, making them more financially capable of addressing any future shocks and stresses.

The solar home system was also fully funded, reducing the energy production cost from USD 2.93/kWh without a grant to USD 1.03/kWh with a grant. The off-grid solar PV at the farm presents an interesting case. Here, the household invested personally in the project, and the RETScreen analysis shows a simple payback period of 7.2 years to recover the investment and an energy production cost of USD 0.323/kWh. In the future, providing grants to similar initiatives undertaken by other farmers would make such projects more financially attractive compared to instances where no grants are provided. This is demonstrated in the third case study—providing a grant of USD 8000 would lead to the immediate recovery of the cost and an NPV of USD 11,700, which is higher than the NPV of USD 3700 when no grant is given.

5. Discussion

Fiji's commitment to addressing climate change is evident through various national policies and strategies, including the Climate Change Act [99], Nationally Determined Contributions (NDCs) [100], Climate Change Policy [101], and the Low Emissions Development Strategy 2018–2050 [95], among others. This study contributes a valuable perspective from the ground level, demonstrating how renewable energy systems are enhancing the resilience of communities in Fiji.

As outlined in Section 1.1, the people of Fiji face significant challenges such as volatile price increases in food and fuel, as well as the impacts of extreme weather events like cyclones and floods. Interviews with the Nasikasika settlement revealed that, during the rainy season (November to June), frequent flooding of the rivers surrounding the settlement disrupts daily life, including access to the settlement and the flooding of agricultural lands (see Figure 11 showing the flooded river on 2 February 2024). These hardships are compounded by the rising costs of essential resources such as food and fuel.



Figure 11. Heavy rainfall caused the river to flood, while strong winds severely impacted the surrounding environment. Photo courtesy of the interviewee.

Both the Nasikasika settlement and the commercial farm case studies underline how the escalating prices of fuel and food are affecting household purchasing decisions. As shown in Table 1, resilience in these communities is significantly enhanced through the integration of renewable energy systems, particularly solar photovoltaics. These systems foster the absorptive, adaptive, and transformative capacities of communities, enabling them to better cope with climate-change-related challenges, environmental disasters, and economic pressures such as rising fuel and food prices.

In terms of financial capital, case studies highlight the substantial economic benefits that solar PV systems bring to households, schools, and communities by replacing fossil fuels (such as diesel and gasoline generators) and kerosene lamps. Additionally, for communities connected to the national grid, the adoption of solar PV reduces electricity bills, providing savings that can be redirected to address urgent needs, such as purchasing materials for rebuilding after cyclones or coping with food price hikes. Similar outcomes have been observed in other countries, such as Bangladesh, where the adoption of solar home systems has contributed to the introduction of income-generating activities, improved social security, enhanced women's empowerment, and a stronger response to natural calamities [102].

These findings highlight the crucial role that renewable energy plays in fostering financial security and adaptive capacities in the face of climate change and economic uncertainty, further supporting the case for greater investment in sustainable energy solutions for vulnerable communities.

Secondly, the solar PV system enhances the physical capital of communities by diversifying their energy sources. For instance, rooftop solar PV systems in single-family homes in

California improve post-earthquake power accessibility year-round [84]. A similar benefit is observed with grid-connected rooftop solar PV systems at the school, which ensures continued electricity availability during cyclones or power outages. Additionally, the biogas system complements the solar PV installation by providing an alternative energy source, particularly for cooking and heating. In emergency situations, where food security becomes a major concern, the ability to prepare meals using biogas helps alleviate some immediate challenges faced by vulnerable populations. Furthermore, the school can function as a community hub during disasters, offering shelter, information, and resources to students and families. By ensuring that critical infrastructure such as schools remains operational, the project fosters interpersonal bonds and strengthens support systems, which are essential during recovery efforts. The school's role as a communication center during emergencies further emphasizes the crucial need for reliable energy availability, allowing evacuees to access electricity when the utility grid is down.

The battery storage capacity at the school enhances its adaptive capacity, further strengthening the school's resilience, as similarly highlighted in [103]. The combination of solar PV with battery storage, as seen in the Nasikasika settlement, ensures that communities retain access to electricity even during cyclones when grid power is typically unavailable. This allows residents to stay connected with family, authorities, and essential news and alerts. Solar home systems enable households to generate their own power, reducing reliance on external sources and ensuring the continuation of critical functions such as lighting, communication, and food refrigeration. A similar conclusion was drawn in ref. [104], which found that solar home systems and solar lamps bolster anticipatory capacity by improving access to weather warnings, enhance absorptive capacity by facilitating post-disaster communication, and support adaptive capacity by providing access to new knowledge. Furthermore, mitigating power supply disruptions—especially during natural disasters—plays a key role in fostering climate-resilient communities [69].

Ref. [105] emphasizes that social capital is strongly correlated with resilience at the community level, particularly through the use of solar energy to engage in community-based disaster preparedness activities. These activities, such as organizing training sessions, conducting drills, and establishing communication networks, foster a culture of preparedness. The ability to rely on renewable energy for such initiatives empowers community members to proactively safeguard themselves against potential threats. Furthermore, the installation and maintenance of solar systems create local employment opportunities, enhancing the community's resilience by building local skills and capacities.

Agriculture, a crucial sector in island communities, is often vulnerable to the effects of climate change and natural disasters. Implementing solar PV systems for irrigation strengthens farm resilience to disruptions in water supply caused by extreme weather events, such as droughts. While traditional, fossil-fuel-powered irrigation systems may fail during disasters, solar-powered systems can continue to operate independently, ensuring crops receive the necessary water even when external resources are limited. This capability is critical for maintaining food security, especially in the aftermath of natural disasters, when access to fresh produce can be severely impacted. The transition to solar-powered irrigation fosters sustainable agricultural practices, essential for long-term resilience. By reducing reliance on fossil fuels, it not only lowers operational costs but also decreases the farm's carbon footprint, supporting climate change mitigation efforts. Embracing renewable energy, the farm sets an example of innovative practices, potentially inspiring other farmers to follow suit. This collective movement towards sustainability can strengthen the resilience of the entire agricultural sector, as farmers share knowledge and resources, adapting together to changing environmental conditions.

This study highlights how solar PV systems and biogas digesters contribute to increasing both the social and cultural capital of communities. The interest generated within families and communities regarding the cost and benefits of these systems signals a transformation toward clean energy. Additionally, the participation of community members in the installation of these renewable energy systems reflects a strong sense of solidarity, an essential factor in effectively responding to natural disasters and climate change. Ref. [106] emphasizes that social relationships influence individual behaviors, foster cooperation, and build solidarity. As observed from community responses, regular cultural events in places like Nasikasika settlement, parent–teacher meetings at schools, and religious gatherings among farmers help bring people together to tackle common challenges. Such activities align with the recommendations from ref. [107], which advocates for increasing social capital through organizing community events and practicing time banking or community currency, providing incentives for volunteers who contribute to collective efforts.

Solar PV and biogas systems play a crucial role in building human capital, as education serves as a primary driver of development [108]. By engaging communities in the operation and maintenance of these systems, individuals acquire new skills—learning not only how to troubleshoot issues but also how to extend the system’s lifespan. This hands-on involvement fosters creativity, thereby enhancing both the adaptive and transformative capacities of the community. The literature frequently underscores that community participation from the outset of energy projects strengthens development and ensures that the benefits of the energy systems are shared widely [109,110]. Education, as highlighted in these discussions, remains a key factor in promoting resilience within communities.

Moreover, the installation of renewable energy systems helps solidify political connections, which can be invaluable during times of disaster response and when addressing climate change impacts. In the case studies, for example, the secondary school benefited from its strong relationship with the Ministry of Education, which facilitated collaboration with other ministries during the solar PV installation. These strengthened ties between the school and policymakers play a significant role in shaping energy policies and market acceptance. Ref. [111] points out that policies and regulations provide a solid institutional framework for renewable energy projects, shaping community and market engagement. Additionally, the alliances fostered through these connections can help promote the transition to renewable energy [112], ultimately enhancing community resilience.

Finally, the natural capital of communities is also bolstered by renewable energy initiatives. Solar PV reduces the carbon footprint, directly contributing to environmental preservation. Biogas digesters, in particular, enhance all three community capacities by facilitating organic waste management and promoting organic farming through the use of digestate slurry. Furthermore, renewable energy improves air quality, which leads to better health outcomes and reduces healthcare costs. This is supported by ref. [113], which highlights the importance of supporting communities reliant on natural resources in protecting ecosystem services, thus better preparing them for extreme events.

In summary:

Absorptive capacity refers to a community’s ability to absorb shocks while maintaining essential functions. For instance, the grid-connected secondary school’s installation of solar PV and biogas systems ensures a stable energy supply, allowing the school to maintain its educational functions and community events during power outages or natural disasters. This mirrors findings from [114], which emphasized the role of solar PV in preserving critical services during emergencies in Iran. On a regional scale, if other schools adopt similar systems, they could collectively enhance the resilience of the educational sector. In the second case study, the 300 W solar home system (SHS) empowers households by providing energy independence, allowing them to continue basic functions like lighting and

communication during grid failures. As ref. [102] highlights, decentralized energy solutions like these give households increased autonomy. The 4.2 kW off-grid solar PV system on the farm, including a water pump for irrigation, ensures continuous food production even amidst fuel price increases. This aligns with [115], which demonstrated that solar-powered irrigation boosts technical efficiency in developing countries' food production. Additionally, the solar PV system powering worker accommodation supports agricultural operations by aiding worker retention. At the national level, renewable energy policies can help create resilient infrastructure, enabling the entire country to better withstand external shocks.

Adaptive capacity refers to the community's ability to adjust to changing conditions over time. In the secondary school case study, the integration of solar PV, biogas, and rainwater-harvesting systems reduces fossil fuel reliance, mitigating climate change and promoting water conservation, as also noted by ref. [116]. This adaptive strategy fosters resilience and helps the school adapt to potential water scarcity. In the off-grid community case, the SHS promotes energy efficiency and independent management, further enhancing community resilience. The farm's solar-powered irrigation system exemplifies climate-smart agricultural practices, reducing reliance on rainfall and helping the farm adapt to drought conditions. Research from Bangladesh [117] confirms that solar-powered irrigation provides co-benefits as an adaptation measure in drought-prone areas. On a regional scale, collaborative community-based projects can enhance adaptive capacity through shared resources and knowledge, and national policies that promote renewable energy innovation and community-driven solutions can strengthen the overall adaptability to energy challenges.

Transformative capacity entails making fundamental changes to energy systems to address long-term stresses and shocks. The secondary school's integrated energy system, which combines solar PV, biogas, and rainwater harvesting, serves as a model for incorporating sustainability into community infrastructure. This innovation not only promotes wider adoption of clean energy technologies but also signals a transition to a circular economy [118]. The adoption of SHS fosters community ownership of energy systems, empowering residents to take control of their energy needs, as also discussed by [49]. Similarly, the farm's adoption of solar-powered irrigation has transformed agricultural practices, improving food security and economic stability. The shift away from fossil fuels shows the potential for community energy solutions to revolutionize agricultural energy use. The off-grid farm model illustrates how decentralized energy can empower rural areas to move away from fossil fuel dependency and reduce reliance on centralized grids. Locally, other farmers adopting similar technologies can cut dependence on non-renewable energy. Regionally, successful case studies could inspire policy changes in agriculture and renewable energy at regional and national levels, promoting sustainable practices and food security strategies.

This study demonstrates that renewable energy (RE) systems are vital for enhancing emergency preparedness and disaster resilience in island communities. By maintaining key infrastructure, such as the solar-powered school, the community can ensure the school serves as a shelter during disasters, supporting emergency response efforts. The SHS case study highlights how households can stay connected with family, friends, and authorities during crises, which is crucial for receiving updates, warnings, and relief instructions. These technologies empower communities to better withstand and recover from natural disasters. Thus, it is essential to prioritize RE systems in disaster preparedness and climate adaptation strategies for island communities.

While the SHS enhances absorptive capacity by providing autonomy over basic energy needs, its relatively small system size (300 W) limits its effectiveness to lighting and phone charging. In contrast, the school's larger-scale solar PV system, combined with biogas and

rainwater harvesting, offers broader absorptive capacity and supports not only essential services but also functions as a community shelter during emergencies. This highlights how more integrated and expansive RE systems enhance a community's ability to handle crises. The SHS potentially reduces energy costs and supports individual adaptive needs, while the school's integrated approach presents a wider shift toward sustainability, influencing circular economy practices and promoting broader adoption of renewable technologies. Meanwhile, the off-grid farm model exemplifies how sustainable agricultural practices contribute to resilience, inspiring broader, regional transformations.

5.1. Comparison with Existing Literature

This study expands the existing literature on community energy systems (CESs) and their role in resilience, particularly within small island developing states (SIDSs). Previous research has explored the impact of renewable energy on disaster preparedness and recovery [104,114], yet this study provides a more comprehensive understanding by examining how CESs enhance different aspects of community resilience—absorptive, adaptive, and transformative—while reinforcing various community capitals.

Our findings align with studies showing the positive effects of solar home systems on household resilience, as seen in Bangladesh [102], Amazonian countries [119], and other developing regions. However, this research adds a unique perspective by exploring the broader benefits of CESs across diverse community settings in Fiji, including schools and agricultural farms. The combination of solar PV with biogas digesters and rainwater harvesting, as demonstrated in the school case study, exemplifies a holistic approach to resilience, resonating with the circular economy concept [118]. This integration promotes resource independence and underscores the potential of CESs not only to provide sustainable energy solutions but also to encourage sustainable practices and effective resource management within communities.

Additionally, this study highlights the often-overlooked role of social capital in enhancing community resilience [105–107]. While technical assessments of renewable energy systems typically focus on energy production and efficiency, our findings suggest that CESs can also strengthen social cohesion by facilitating collective action, knowledge sharing, and community engagement. This is especially vital in SIDSs such as Fiji, where close-knit communities are crucial for navigating and responding to natural disasters and the challenges posed by climate change.

By focusing on the specific context of Fiji, this research addresses a gap in the literature on CESs within developing nations [37]. The insights derived from these findings offer valuable guidance to policymakers and practitioners in Fiji and other SIDSs who seek to implement CESs as a strategic tool for fostering community resilience.

5.2. Limitations of the Study and Scope for Future Research

This study acknowledges several limitations that suggest promising directions for future research. The qualitative nature of this study, which relied on semi-structured interviews with only three communities using renewable energy technologies that were conveniently accessible, limits the generalizability of the findings. A broader sample in future research, encompassing a diverse range of communities across Fiji and other SIDSs, utilizing various renewable energy technologies, would provide a more comprehensive understanding of the complex relationship between community energy systems (CESs) and community resilience.

While this research provides valuable qualitative insights, future studies could adopt a mixed-methods approach, combining qualitative data with quantitative measures. Collecting data on energy consumption, economic benefits, social outcomes, and environmental

impacts would strengthen the analysis and allow for a more robust evaluation of CES contributions to community resilience.

Another key area for future investigation is the role of different stakeholders in CES development, including government agencies, NGOs, and the private sector. Examining the policy landscape, financing mechanisms, and community engagement strategies will enhance our understanding of the factors influencing the successful implementation and scaling of CESs in building resilience.

Extending future studies to include more diverse renewable energy sites and their impact on local populations and livelihoods would enhance the potential to generalize findings to other SIDSs. Additionally, integrating advanced computational frameworks, such as deep reinforcement learning, exploring freshwater–energy integration through solutions like hydrothermal simultaneous transmission, and addressing multi-uncertainties [40] could further enrich CES studies. These approaches would offer a holistic view of enhancing resilience and overcoming the complex challenges faced by small island nations.

Finally, further research could explore the long-term impacts of CESs on community well-being, social equity, and environmental sustainability. Longitudinal studies tracking the evolution of community resilience over time would provide valuable insights into the adaptive and transformative capacities of CESs, particularly in the context of climate change and other emerging challenges. By addressing these limitations and pursuing the suggested avenues for research, future studies could build a more comprehensive understanding of the critical role of CESs in promoting resilient, sustainable communities in SIDSs and beyond.

5.3. Policy Recommendations

The following policy recommendations are derived from the study's findings:

- **Incentivize and Support CES Adoption:** Provide targeted grants, subsidies, tax breaks, or low-interest loans to encourage the adoption of renewable energy technologies, particularly in rural and remote areas. This support should be extended to households, institutions, communities, and farmers, enabling broader access to clean energy solutions.
- **Conduct Public Awareness Campaigns:** Launch comprehensive awareness campaigns to educate individuals and communities about available sustainable energy technologies. These campaigns should highlight the transformative potential of renewable energy to improve livelihoods, enhance resilience, and promote long-term sustainability.
- **Enhance Capacity Building:** Invest in robust capacity-building programs that equip community members with the necessary skills to operate and maintain renewable energy systems. By enhancing local expertise, these programs ensure the sustainability and longevity of community energy systems (CESs).
- **Conduct Research and Development:** Prioritize research and development initiatives focused on innovative renewable energy technologies. These efforts should be tailored to the unique needs and challenges faced by Fiji's diverse communities and environments, fostering solutions that are locally relevant and sustainable.
- **Strengthen Cross-Sector Collaboration:** Promote collaboration between government agencies, non-governmental organizations (NGOs), private sector actors, and communities. This multi-stakeholder approach will enable the sharing of expertise, resources, and best practices, thus accelerating CES development and increasing the impact of renewable energy initiatives.
- **Boost Meaningful Community Engagement:** Implement participatory planning processes that give communities a genuine voice in the design and implementation of

CES projects. Ensuring that local populations are engaged in decision making helps create solutions that are culturally appropriate and better suited to community needs.

- **Promote Energy Access as a Social Equity Issue:** Frame energy access as a fundamental human right and ensure that policies and programs are designed to address the needs of marginalized and disadvantaged communities. This perspective can help create inclusive strategies for increasing energy access and resilience.

By implementing these recommendations, Fiji and other developing island nations can leverage community energy systems to enhance energy access, foster community resilience, and support sustainable development in the face of climate change and other pressing challenges.

6. Conclusions

The community resilience framework offers a comprehensive approach to understanding the interconnected factors that contribute to community development and resilience. By recognizing and investing in all seven capitals, communities can embark on a more holistic and sustainable path toward fostering long-term well-being and resilience. This framework challenges traditional, siloed development strategies, advocating for a more integrated and collaborative approach that acknowledges the interdependence of social, economic, environmental, and cultural dimensions.

Through the three case studies explored in this research, it is evident that renewable energy initiatives significantly enhance community resilience. These initiatives strengthen communities' absorptive, adaptive, and transformative capacities, helping them better withstand natural disasters, mitigate the effects of climate change, and adapt to fluctuations in goods and services. The findings reinforce the imperative to expand access to renewable energy, including electricity and clean cooking solutions, in underserved communities.

While renewable energy is typically viewed as a climate change mitigation strategy, this study emphasizes its critical role in enhancing communities' resilience. Renewable energy initiatives not only support adaptation and resilience to stresses and shocks but also help communities thrive amidst these challenges. One case study, focusing on solar PV systems for irrigation, highlighted the vital role of human capital in building resilience. It underscored how innovative technologies and knowledge sharing contribute to communities' adaptive capacity.

This research stresses the importance of integrating renewable energy systems into community infrastructure to strengthen resilience on multiple scales—from individual households to national policy. By highlighting the tangible benefits of renewable energy systems in Fijian communities, this study provides valuable insights for policymakers, practitioners, and communities seeking to enhance resilience to climate change and other related challenges in Fiji and other vulnerable regions.

The findings from this research can serve as a guiding resource for decisionmakers, encouraging the inclusion of renewable energy and energy efficiency strategies in policies aimed at improving community resilience. When developing climate change adaptation strategies and enhancing sustainable development indices, government departments, NGOs, the private sector, and other stakeholders should prioritize sustainable energy solutions to support resilient communities.

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