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Powering through the storm: Assessing the resilience of electricity sociotechnical systems in typhoon-impacted coastal communities

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ABSTRACT

The increasing frequency and severity of extreme weather events pose significant challenges for coastal communities in typhoon-prone regions of the Philippines, particularly in maintaining reliable electricity systems. This paper investigates the interactions among hazards, vulnerabilities, and risks that characterise the sociotechnical frameworks of electricity systems in the Calamianes Islands of Palawan. We employed qualitative research methods, including interviews and focus group discussions, to illustrate how typhoons exacerbate existing vulnerabilities, resulting in heightened risks to electricity infrastructure. Our key findings indicate that additional hazards like storm surges and landslides cause substantial damage to electrical assets. Concurrently, technical vulnerabilities—such as ageing infrastructure and limitations within the workforce—intensify these impacts. Moreover, social vulnerabilities, which include household socioeconomic status and communication barriers, further complicate the resilience of these systems. Disruptions to electricity supply originate from physical damage and the interconnectedness of essential services, leading to cascading effects on community well-being. We underscore the necessity of adopting an integrated approach to disaster risk management that considers the sociotechnical dimensions of electricity systems. These insights are crucial for enhancing the resilience of electricity systems in the face of climate change and emerging challenges.

1. Introduction: enhancing the resilience of electricity systems against climate-induced disruptions

A continuous and reliable supply of electricity is essential for the functioning of modern societies and economies [1]. This necessity is particularly pronounced in communities vulnerable to extreme weather events such as typhoons, which frequently disrupt electricity provision and adversely affect critical infrastructure, essential services, and economic productivity [2]. Moreover, the sociotechnical systems governing electricity, encompassing technical infrastructure alongside social, organisational, and institutional dimensions, are increasingly susceptible to disruptions from extreme weather conditions [2,3,13,21]. Consequently, there is a pressing need to undertake a comprehensive re-evaluation of our strategies for ensuring the resilience of energy supply in light of climate-related challenges.

In this study, enhancing resilience refers to the active strengthening of electricity infrastructure, examined through sociotechnical systems, to effectively withstand the impacts of typhoons and other extreme weather events (cf. [4]). This approach safeguards the safety, well-being, and long-term economic development of affected communities; hence, re-evaluating this aspect is paramount given that the increasing frequency and intensity of extreme weather events jeopardise the fundamental reliability of these essential systems [5].

To systematically re-evaluate and enhance resilience, it is essential to comprehend the specific challenges encountered by sociotechnical systems in electricity. Extreme weather events, such as typhoons, pose various risks, including damage to power lines and disruptions in service delivery [6,7,8,9]. These physical hazards reveal inherent vulnerabilities present within the sociotechnical electricity system. Vulnerability, commonly defined as a combination of risk and resilience within energy security frameworks [10], signifies the susceptibility of a system to disruption when confronted with a threat or hazard [11].

It is crucial to note that these vulnerabilities extend beyond mere technical aspects, such as aged infrastructure or physical damage to equipment, to encompass social dimensions, including socioeconomic inequalities and inadequate communication networks within communities. The interaction between hazards and vulnerabilities generates risks, which are defined as the consequence of a hazard interacting with

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elements that predispose individuals and locations to exposure [12]. In coastal communities that experience frequent typhoons, this interaction results in risks such as widespread interruptions to the supply and distribution of electricity.

Electricity infrastructures in coastal communities, especially those vulnerable to typhoons, serve as examples of intricate sociotechnical systems that integrate technological elements with social dynamics [2,13,21]. Examining these systems through a sociotechnical lens is essential for comprehending resilience in extreme weather events [14,20]. Such a perspective transcends a purely technical view of the electricity system, acknowledging its social embedding. This integration underscores that enhancing resilience necessitates promoting collaboration among various stakeholders and prioritising community engagement and technical advancements to ensure alignment with local needs and capabilities, ultimately improving overall robustness [2,15,59].

Addressing hazards, vulnerabilities, and risks (HVRS) is essential for enhancing the resilience of electricity sociotechnical systems. This viewpoint corresponds with the broader debate on risk and uncertainty within energy systems, where risk assessment is deemed crucial for ensuring energy security [10]. Recognising risk in climate-induced disruptions is essential, focusing on the interactions between identified hazards and technical or social vulnerabilities. This approach further highlights the significance of understanding interconnectedness and cascading effects, which are critical components of systemic risk discussed in the wider energy security literature [10].

Enhancing resilience is fundamentally associated with long-term sustainability, which constitutes one of the core dimensions of energy security [10]. Addressing disruptions induced by climate change directly contributes to the environmental sustainability of energy supply while fostering energy security, which is defined as a state of low vulnerability in critical energy systems. This vulnerability emerges from the interplay between risk and resilience [10]. By identifying crucial areas for intervention—including infrastructure enhancement, emergency response planning, and the social aspects of electricity systems—we can establish a more robust framework for managing impacts, safeguarding community well-being and promoting sustainable development.

This study consequently investigates the following research question: **What hazards, vulnerabilities, and risks (HVRs) are linked to electricity sociotechnical systems in the Calamianes Islands of Palawan, Philippines?** The aim is to uncover critical insights that will guide the development of more resilient infrastructure, which is vital for safeguarding the safety, well-being, and long-term economic stability of these coastal communities vulnerable to typhoons.

This paper is organised as follows: Section 2 explores electricity as a sociotechnical system and outlines the analytical framework, integrating insights from sustainability and risk literature. In Section 3, we present the study sites and the employed methodology. Section 4 details the climate-related hazards associated with sociotechnical electricity systems in the Calamianes Islands. Subsequently, Section 5 identifies vulnerabilities, categorised into technical and social dimensions. Section 6 accentuates the risks inherent in electricity sociotechnical systems. Following this, Section 7 examines potential solutions and policy implications. Finally, Section 8 addresses the conclusion, limitations of the study, and opportunities for further research, proposing avenues associated with the theoretical concepts discussed.

2. Background: understanding the HVRs of electricity sociotechnical systems in typhoon-prone coastal communities: an analytical framework

Analysing the electricity infrastructure as a sociotechnical system provides essential insights into typhoons' hazards to coastal communities. Hazards refer to the potentially damaging physical events or phenomena, such as extreme winds, flooding, and storm surges associated with typhoons [2,19,51]. Vulnerabilities denote the characteristics of the system or community that render them susceptible to the impacts of these hazards [11].

According to energy security frameworks, vulnerability combines risk and resilience [10]. Within sociotechnical electricity systems, we can categorise vulnerabilities into two primary domains: technical and social [20,21]. Technical vulnerabilities encompass issues related to physical infrastructure, such as damage to generation, transmission, and distribution components, as well as system operation and management challenges [20,21]. Conversely, social vulnerabilities involve factors such as socioeconomic disparities, challenges in geographic accessibility, and limitations in information and communication systems [22]. The concept of susceptibility, which refers to the likelihood of a threat or hazard disrupting the electricity system, constitutes a crucial element in assessing vulnerability [11].

Risk refers to the potential consequences of interacting hazards and vulnerabilities [12]. In the context of electricity sociotechnical systems within typhoon-prone coastal communities, identified risks encompass disruptions to supply and distribution, which originate from physical damage, cascading effects, interdependencies with other critical infrastructures [2], social vulnerabilities, and the deterioration of ageing infrastructure [REF20, 21, 44]. A holistic understanding of these interdependencies and cascading impacts assumes particular significance, as they pertain to systemic risk, an under-researched yet vital aspect of energy security that examines interconnected vulnerabilities across diverse systems [10].

This study employs an analytical framework to elucidate the interconnected HVRs within the broader sociotechnical system. This framework is illustrated in Fig. 1 and highlights the hazards, vulnerabilities, and risk factors associated with electricity vulnerability, typhoons, and coastal communities. This approach facilitates the identification of critical areas requiring intervention, including the upgrading of infrastructure, the enhancement of emergency response plans, and the development of community engagement strategies in disaster preparedness initiatives. Integrating both the technical and social dimensions of electricity systems fosters the creation of more effective risk management strategies.

This approach aligns with the understanding of energy security as comprising reliability, affordability, and sustainability [24,45], with resilience playing a crucial role in enhancing both reliability and the long-term dimensions of environmental sustainability. The HVR framework, viewed through a sociotechnical lens, facilitates a systematic and transparent evaluation of risks associated with climate hazards and systemic vulnerabilities, thereby contributing to a more holistic understanding of energy security in regions highly susceptible to climate impacts. Identifying and addressing HVRs within this sociotechnical context enables the formulation of effective strategies to build resilience, bolstering energy security and promoting the sustainability and well-being of coastal communities.

This framework also partly and normatively engages with the broader theoretical discourse on energy futures. Resilient infrastructure development is shaped by dominant and alternative sociotechnical imaginaries [16,17,18]. Sociotechnical imaginaries are collective visions of future energy systems that significantly influence priorities and policies, co-produced by science, technology, and society [16]. For example, an imaginary prioritising large, centralised, and robust infrastructure will likely lead to distinct resilience strategies compared to one promoting distributed, community-controlled renewable energy systems [17,18,23].

We recognise the normative dimensions of these imaginaries to understand how various stakeholders perceive HVRs and envisage resilient futures. This understanding is crucial for designing policy strategies that are technically rigorous, socially accepted, and equitable. We use the study's examination of HVRs in the Calamianes Islands and the empirical data it offers to develop policy recommendations.

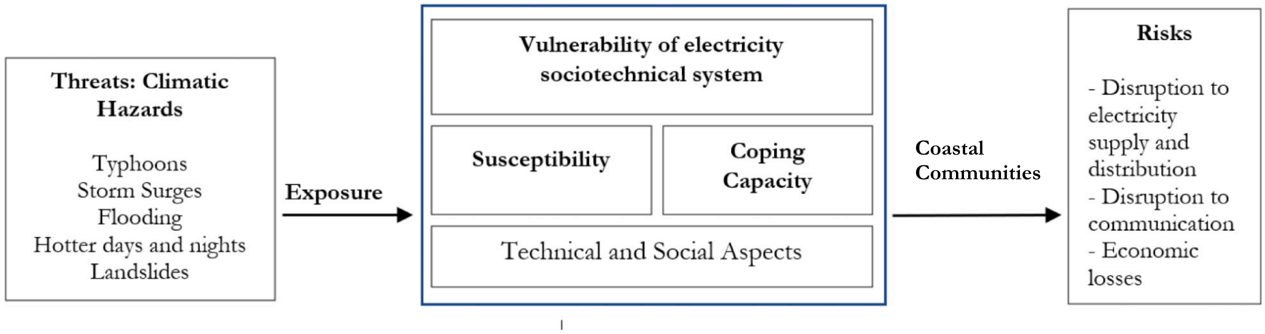

Fig. 1. An HVR framework for understanding the vulnerabilities of electricity sociotechnical systems in typhoon-prone coastal communities. Source: The Authors.

3. Study sites and methodology

To address the research question, we analysed selected communities within the typhoon-prone coastal regions of the Calamian Islands (3.1). We employed a qualitative methodology (3.2) to gain in-depth insights and a contextually rich understanding of the hazards, vulnerabilities, and risks encountered. Data collection persisted until saturation was achieved; at this point, no additional information could be gathered. This research received approval from the Human Research Ethics Protocol Committee of the Hong Kong University of Science and Technology on December 5, 2022 (HREP Number 2022-0308).

3.1. Study locations: typhoon-prone communities of the Calamian Islands

This study was conducted in the Calamianes Group of Islands in the Province of Palawan, in western Philippines. The three primary islands comprising the Calamianes are Busuanga, Culion, and Linapacan. These islands lie between the South China Sea/West Philippine Sea to the west and the Sulu Sea to the east (see Fig. 2). Due to constraints related to location, time, and accessibility, our study focuses only on Busuanga, Coron, and Culion islands. The municipality of Coron is positioned within the main island of Busuanga.

3.1.1. Study site 1: Busuanga Island

Busuanga Island is the largest island in the Calamianes archipelago. The municipality's Comprehensive Land Use Plan [26] indicates that the

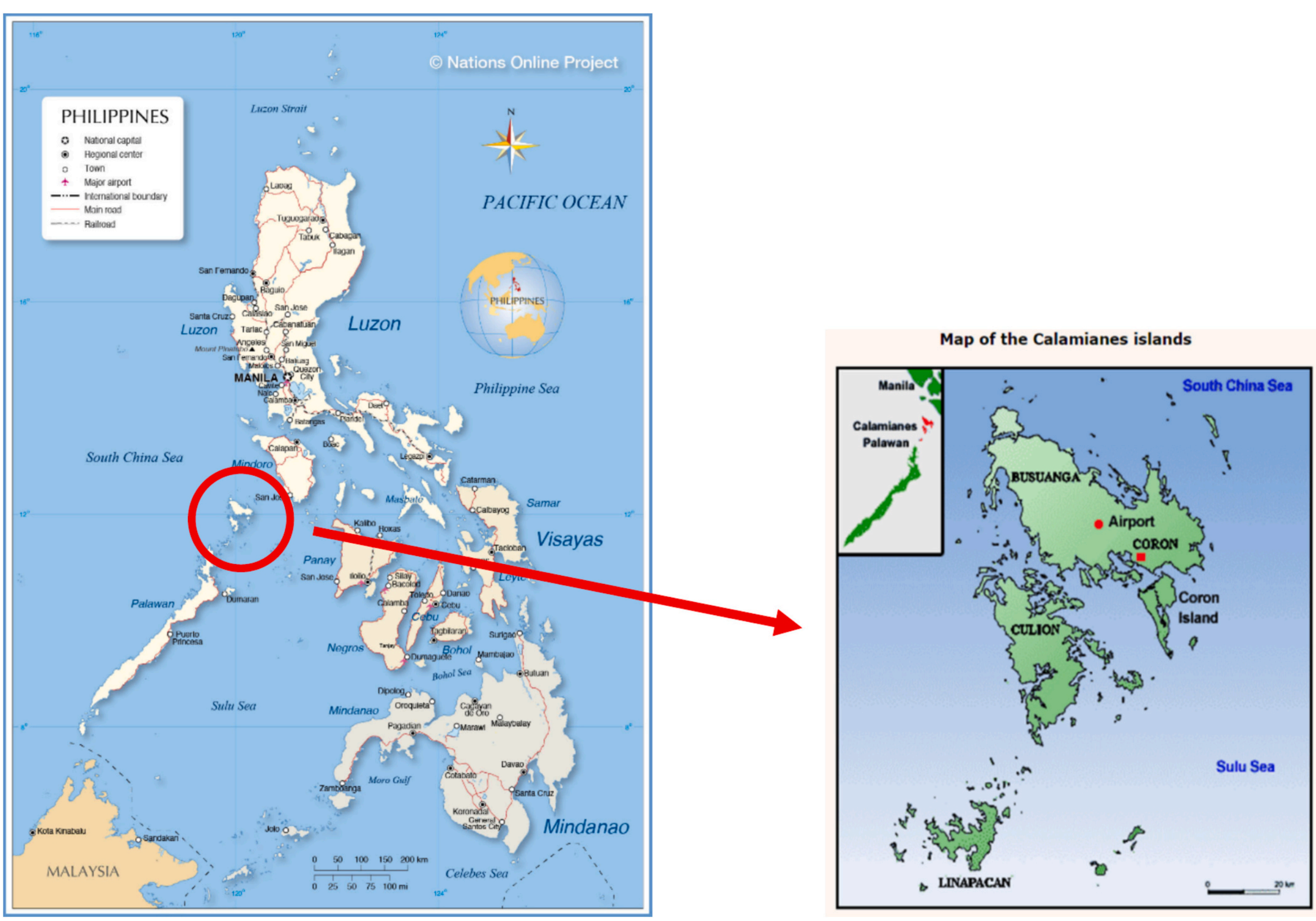

Fig. 2. Study Location: The Calamianes Islands, Palawan, Philippines [25].

island's total land area encompasses 52,748 ha. This island hosts the primary airport, Francisco B. Reyes Airport, which facilitates visitor access to the Calamianes. Additionally, Busuanga Island ensures connectivity through land transportation originating from Coron Island.

The Municipality of Busuanga comprises fourteen barangays and numerous islets. It is predominantly inhabited by the Indigenous Peoples of Palawan, known as the Tagbanuas. Additionally, the municipality is esteemed for its picturesque beaches and the unique Calauit Island. In 1976, the government designated it as an island game preserve and wildlife sanctuary through Presidential Proclamation No. 1578, aimed at protecting endemic and exotic animal species.

3.1.2. Study site 2: Coron Island

Coron Island is one of the three municipalities within the Calamianes Group of Islands and is recognised as a first-class municipality in the Province of Palawan. The municipality encompasses a total land area of 72,309.53 ha and borders the municipality of Busuanga. The town centre of Coron is readily accessible via various land transport options from Busuanga Airport. A ferry service operates from mainland Palawan, specifically through El Nido port, with an approximate travel duration of 6 h to Coron Pier. Coron comprises seven urban barangays and 16 rural barangays, among which five are designated as island barangays. According to the 2015–2016 Coron CBMS Census, the municipality supports 8075 households and exhibits the highest population growth rate of 3.82 % in the Province of Palawan [27].

3.1.3. Study site 3: Culion Island

Established as a leprosarium in 1906 during the American colonial regime, Culion Island remained under the designation of ‘leprosy-endemic’ until the World Health Organisation declared it free of the disease in 2006 [28]. The municipality covers an area of 500 km^2 and is bordered to the north by Busuanga Island, to the east by Coron, and the south by the Linapacan Islands. It comprises fourteen barangays and is home to 23,213 residents, as recorded in the 2020 census. Access to Culion Island is exclusively by sea, with ferry boats operating from Busuanga and Coron Islands. Furthermore, Culion Island is home to the Culion Sanitarium and General Hospital, which serves as the sole general hospital for all of Northern Palawan [29].

3.2. Qualitative data collection approaches

3.2.1. Participant recruitment and selection for key informant interviews

Method 1 involved conducting key informant interviews with specialists from national, provincial, and local government bodies, as well as representatives from non-governmental organisations and local electricity distributors. These interviews followed a structured guide examining experiences, perceptions, and coping strategies regarding extreme weather events and electricity resilience. The process unfolded in three distinct phases. The first phase occurred between December 2022 and January 2023; the second phase took place from June to July 2023; and the final phase was completed between December 2023 and January 2024.

Author Eireka Orlido Meregillano systematically identified and recruited key informants from national, provincial, and local government institutions, as well as from non-governmental organisations and local electricity distributors. These informants included officials from the Municipal Planning and Development Office, the Municipal Disaster Risk Reduction Office, and the Tourism Office. Additionally, representatives from the electric cooperative board of directors contributed, alongside prominent officials from the Municipal Tourism Office and the Municipal Disaster Risk Reduction Office. Furthermore, individuals from the Renewable Energy and Hydrothermal Division and the Planning Division of the Philippines Department of Energy participated in the interviews. Eireka engaged these individuals directly through their professional networks and the official channels relevant to the research topic.

Key informants were selected due to their key positions and their possession of specialised knowledge and perspectives concerning experiences, perceptions, and coping strategies related to extreme weather events in the context of electricity resilience. Local government officials (KI1, KI2) were chosen for their involvement in planning and disaster management at the community level. Representatives from the electric cooperative (KI3, KI5) played a crucial role owing to their direct engagement in electricity provision and infrastructure. Tourism officials (KI4, KI6) contributed insights regarding the impacts on a significant economic sector. Representatives from the Department of Energy (KI8, KI9) offered a national-level perspective on energy planning and renewable energy. The selection process aimed to encompass stakeholders from various governance levels and key sectors pertinent to electricity resilience.

The selection of key informants sought to encapsulate a diverse range of perspectives from entities directly involved in or affected by electricity resilience in the typhoon-prone coastal regions of the Calamian Islands. Representatives from various governmental levels, the energy provider, and a significant economic sector were incorporated to ensure a comprehensive understanding of challenges and potential solutions from multiple viewpoints. We conducted interviews until data saturation was reached, culminating in nine interviews (see Table 1). Eireka conducted face-to-face interviews in the municipalities of Busuanga, Coron, and Culion during two distinct phases: the first phase occurred on 20 December 2022, while the second phase was conducted from June to July 2023, with Filipino as the primary language of communication. The final phase of interviews took place via the Zoom platform from December 2023 to January 2024, utilising both English and Filipino. The interview guide is included in Appendix 1.

3.2.2. Participant recruitment and selection for focus group discussions (FGDs)

Method 2 comprised FGDs that actively engaged community leaders, vulnerable individuals, such as older people and those with disabilities, and stakeholders from the education and livelihood sectors. Community leaders, who participated in FGDs 1 to 9, were included due to their understanding of local dynamics and community needs. Representatives from various barangay sectors in FGDs 2 and 5 contributed perspectives reflecting diverse community segments. Including vulnerable individuals ensured the capture of experiences from those most susceptible to electricity disruptions. Additionally, stakeholders from the education and livelihood sectors provided insights into how these crucial aspects of community life are affected by, and respond to, electricity-related challenges during extreme weather events. Table 2 presents a summary of the group discussions.

Eireka facilitated face-to-face discussions in two phases: the initial phase was conducted on 20 December 2022, followed by a second phase

Table 1
Key informants and their brief descriptions.

Informant codes	Informant descriptions
KI1	A local government official in the Municipal Planning and Development Office of one of the 3 studied municipalities
KI2	A local government official in the Municipal Disaster Risk and Reduction Office of one of the 3 studied municipalities
KI3	A member of the electric cooperative board of directors
KI4	A representative from the Tourism office of one of the 3 studied municipalities
KI5	Area manager of the electric cooperative office in one of the 3 studied municipalities
KI6	Key official in the Municipal Tourism Office
KI7	Key official at the Municipal Disaster Risk Reduction Office
KI8	A representative of the Renewable Energy and Hydrothermal Division of the Philippines Department of Energy
KI9	A representative of the Planning Division of the Philippines Department of Energy

Table 2
FGD Codes and their brief descriptions.

FGD codes	Descriptions and details of FGDs
FGD1	Six barangay (village) community leaders (3 males, 3 females)
FGD2	Five representatives of barangay sector (2 males, 3 females)
FGD3	Five barangay community leaders (2 males, 3 females)
FGD4	Five barangay community leaders (2 males, 3 females)
FGD5	Four representatives of barangay sector (4 females)
FGD6	Five barangay community leaders (3 males, 2 females)
FGD7	Six barangay community leaders (2 males, 3 females)
FGD8	Six barangay community leaders (1 male, 5 females)
FGD9	Six barangay community leaders (1 male, 5 females)

from June to July 2023. Filipino served as the primary medium of communication. The discussion guide is included in Appendix 2.

The semi-structured questions during these discussions examined participants' experiences, perceptions, and coping strategies relating to extreme weather events and their effects on electricity resilience. Participants frequently shared their experiences and coping strategies regarding electricity disruptions during these events, indicating a consensus at the community level. For example, there was widespread acknowledgement of the challenges of prolonged power outages on livelihoods and daily activities. However, discussions revealed diverse opinions, particularly concerning potential solutions and the perceived effectiveness of current measures. These differing perspectives reflected the varied vulnerabilities and priorities of different community segments. Acting as facilitators, the authors ensured that all viewpoints were acknowledged, and observations regarding these dynamics were documented for further analysis of the transcripts.

All interviews and FGDs were meticulously recorded and transcribed. Interviews conducted in Filipino were transcribed into spoken Filipino and accurately translated into English. Eireka managed both transcription and translation to ensure consistency throughout the dataset. The transcripts underwent coding using MAXQDA version 2020. Furthermore, an initial phase of free coding was applied to the transcripts. In the subsequent round, the initial codes were regrouped and analysed to identify synthesised key themes, enhancing the depth and clarity of the findings.

4. Climate-related hazards associated with electricity sociotechnical systems in the Calamianes Islands

We identified six categories of hazards linked to electrical systems in coastal Calamianes. Table 3 provides the frequency codes for each identified hazard, which we will discuss next.

4.1. Typhoon hazards

The code "typhoon" refers to a specific climatic hazard characterised by intense winds, substantial rainfall, and storm surges. It is the most frequently mentioned hazard in the interviews, accounting for 35.85 % of all participant groups. Table 4 presents a detailed account of the typhoons recorded at the study sites.

Notably, Typhoon *Yolanda* (International name: Haiyan), classified as a Category 5 super typhoon, was referenced 22 times, constituting

Table 3
Code frequencies for climate-related hazards.

Hazards	Code frequency	Percentage
Typhoons	19	35.85
Storm surges	14	26.42
Landslides	7	13.21
Strong winds	6	11.32
Flooding	5	9.43
Hotter days and nights	2	3.77
Total	53	100

Table 4
Typhoons recorded at the research locations [30].

Local names	International names	Description/ category	Year	Frequency of mention	Percentage
Yolanda	Haiyan	Super typhoon, Category 5	2013	22	61.11
Undang	Agnes	Typhoon, Category 4	1984	6	16.67
Paeng	Nalgae	Severe tropical storm, Category 1	2022	3	8.33
Rosing	Angela	Super typhoon, Category 5	1995	2	5.56
Odette	Rai	Super typhoon, Category 5	2021	2	5.56
Auring	Hilda	Tropical depression	1999	1	2.77
Total				36	100

61.11 % of the occurrences in the transcripts. Other notable typhoons include Typhoon *Undang* (Agnes), a Category 4 storm mentioned six times (16.67 %), and Typhoon *Paeng* (Nalgae), a Category 1 storm from 2022, which was recorded three times (8.33 %). Furthermore, Typhoons *Rosing* (Angela) and *Odette* (Rai), both Category 5 super typhoons that occurred in 1995 and 2021, respectively, were mentioned twice each, representing 5.56 %. Finally, Typhoon *Auring* (Hilda), a tropical depression in 1999, accounted for 2.77 %. Our analysis identified 36 coded instances of typhoons, highlighting their significance in the respondents' discourse.

The participants underscored the dynamic nature of weather patterns, with KI6 and KI7 noting the rising prevalence of typhoons. K16 expressed, *"I am often astonished by how significantly our weather fluctuates. The rainy season typically commences in June, coinciding with the start of the school year. However, this year, the rain appears to have arrived later than usual, only beginning during the third or fourth week of the month."* K17 remarked, "*In the Calamianes Islands, we generally experience around three to four typhoons yearly, but I have noticed an increase in frequency recently."*

Respondents predominantly characterised their experiences with extreme typhoons through the lens of Super Typhoon Haiyan, which devastated the Philippines in 2013. This event's significance is highlighted by its severe impact, particularly in Palawan province, where the Provincial Disaster Risk Reduction and Management Council declared eleven municipalities to be in a "state of calamity" following the storm's destructive passage [31]. Among the most severely affected were Busuanga, Coron, and Culion. K17 remarked, "*For us, the most devastating typhoon we have ever faced was Yolanda, also known as Haiyan."* Participant 1 from Culion's FGD1 shared, *"Having grown up here, I vividly remember my first real encounter with Typhoon Yolanda; it was a powerful storm that left an indelible mark on me."*

The escalating frequency and intensity of typhoons, alongside the noted irregularity of weather patterns, pose significant threats to the resilience of electricity systems in coastal communities [32]. These climatic phenomena significantly damage electricity infrastructure, including power lines, transformers, and distribution networks. KI5 described the profound helplessness experienced during Typhoon Haiyan, sharing: "*When Typhoon Yolanda struck, darkness enveloped everything. Nearly all our electric lines were incapacitated—about 95% suffered damage. We sat idle, powerless, as the storm obliterated our power infrastructure. It was an incredibly challenging period for us."* This perspective aligns with a news report indicating that approximately 80 to 90 % of electric power lines in the municipality of Coron were rendered inoperative due to the typhoon's impact [33].

4.2. Storm surge hazards

Storm surges denote temporary elevations in sea level during storms, primarily resulting from the combination of strong winds and reduced atmospheric pressure [51]. This hazard ranked second among the identified codes, with 26.42 % of respondents indicating personal experiences or knowledge of others' experiences regarding this phenomenon. Storm surges frequently coincide with typhoons, posing significant threats to coastal regions [34,51].

Two female participants provided detailed accounts of their experiences with storm surges. Participant 1 from FGD9 recounted her experience during Typhoon Yolanda (Haiyan): *"Our household only experienced a storm surge during Yolanda. Living near the coast, we witnessed the vastness of the waves firsthand."* Similarly, Participant 4 from FGD8 described the rising seawater at the onset of Typhoon Haiyan, a situation exacerbated by the high tide. She expressed: *"As Yolanda approached, seawater surged dramatically, intensified by the high tide, which made the situation even more precarious."* A male participant 1 from FGD5, who serves as a barangay captain, highlighted the issue of storm surges in remote island barangays: *"The island barangays faced not only the devastation of their houses but also the absence of designated evacuation facilities."*

Participant accounts illuminate the ramifications of storm surges, particularly the devastating effects of Typhoon Haiyan. In electricity systems, storm surges significantly disrupt operations, particularly through the inundation of power substations and resulting load losses [35]. However, the study sites observed that storm surges did not directly impact the electricity power substations. Instead, their primary effect was on the homes situated in coastal areas, where seawater inundation rendered power outlets inoperable.

A female Participant 4 from FGD8 reflected on her experience: *"During Typhoon Haiyan, the storm surge coincided with high tide. Water flooded into our home, making the power outlets utterly unusable. It was dangerous with the wet conditions."* Participant 5 from FGD8 recounted: *"To mitigate damage from storm surges and high tides, we elevated our power outlets as much as possible. Despite our efforts, the ferocious winds of Typhoon Haiyan made it nearly impossible to keep the outlets dry."*

4.3. Landslide hazards

Although landslides are not categorised as direct climatic hazards, they strongly correlate with typhoons and heavy rainfall, significantly intensifying their frequency and severity. This association renders landslides the third most cited hazard in the interviews, comprising 13.21 % of all hazard-related codes. Respondents recognised the occurrence of landslides, noting that these events tend to be limited to specific areas and are primarily instigated by typhoons and prolonged heavy rain. Participant 3 from FGD5 expressed this connection poignantly: "*When the rain falls incessantly, landslides become a reality. Our community recently faced a landslide that claimed several homes, deeply impacting many of us.*"

Participant 3 from FGD8 recounted a significant incident involving a landslide during a major typhoon, underscoring the connection between typhoons and landslides. *"I distinctly remember witnessing a landslide during Typhoon Undang,"* she remarked. K17, an official from the Municipal Disaster Risk and Reduction Management Office, supported these accounts, explaining that small-scale landslides on Culion Island frequently arise from soft soil conditions, particularly during typhoons and heavy rainfall. K17 described their proactive strategy for addressing this issue, prioritising rehabilitating and retrofitting at-risk areas through effective drainage management. This approach aims to reduce the risk of landslides and enhance community safety.

A landslide is the movement of rocks, debris, or earth down a hill or slope [36]. In regions prone to landslides, residential structures, buildings, and electrical infrastructure face significant risks, as such events can severely impact power plants, substations, and transmission lines, ultimately disrupting the electricity supply. The remoteness and inaccessibility of certain *barangays* (villages) within the study area further complicate recovery efforts; landslides hinder the restoration of damaged electricity lines and poles, resulting in prolonged outages. As KI5, the area manager for the local electric cooperative, noted: "*After Yolanda, we faced considerable challenges navigating blocked roads due to landslides and fallen trees. It was difficult, but we persevered to assess the damage and initiate repairs to our electric lines as soon as possible.*"

In addition to landslides, strong winds characterised by high-speed gusts commonly associated with typhoons threaten electricity infrastructure. Approximately 11.32 % of interviewees reported experiencing such winds during Typhoon Haiyan. Participants vividly recounted the intensity of the winds, with a male Participant 2 from FGD8 stating, "*The wind felt wild, almost like a tornado. I could hear it whistling past me.*" Similarly, two male participants—i.e., Participant 1 from FGD8 and Participant 2 from FGD5—expressed their feelings regarding the powerful winds during the same typhoon, stating, *"When Yolanda hit us, we truly felt the force of those winds."*

The detrimental effects of strong winds on electricity systems are extensively documented in the literature, including the collapse of communication towers [37] and damage to overhead transmission and distribution lines caused by debris propelled by high winds [32,37]. These impacts were particularly evident following Typhoon Haiyan, as a female Participant 3 from FGD2 shared: *"The powerful winds from Typhoon Haiyan uprooted many trees and brought branches crashing down, damaging our homes, electric poles, and power lines."* Participant 2 from FGD2 remarked, "*The electric lines snapped under the intense weather. This truly highlighted the power of nature!*"

4.4. Flooding hazards

Flooding refers to the submergence of land due to the accumulation of water, typically caused by heavy rainfall or storm surges. Approximately 9.43 % of interviewees reported experiencing flooding during typhoons and periods of significant rainfall. It is essential to emphasise that flooding within the three study sites primarily affects specific areas, particularly agricultural regions, and is characterised as an infrequent event.

For example, KI7 expressed the significant challenges of flooding in the heart of Culion, specifically in Barangay Malaking Patag. He remarked, *"Many of us face difficult times in our community. The local farmers are struggling severely as their agricultural lands and rice crops suffer. Without an efficient drainage system, our rice fields often become submerged, which presents real challenges for families relying on farming for their livelihood."* K17 further pointed out that the water storage facility meant to supply the barangay is inadequately functional, causing rainwater to flow directly into farmlands rather than being properly stored or channelled.

Participant 1 from FGD7 expressed similar concerns, noting that flooding predominantly occurs in the coastal region during heavy rainfall in the central areas of their barangay. He highlighted the urgent necessity for effective drainage systems to address this issue. The relationship between flooding and typhoons is particularly pronounced, as these meteorological events contribute to significant rainfall, intensifying flooding in targeted locales. Although flooding in the study sites is confined and primarily affects agricultural zones, it is crucial to grasp the broader repercussions and implications of such flood occurrences, especially regarding farmer livelihoods (cf. [50]).

Interestingly, the study revealed no accounts detailing the direct impacts of flooding on the electricity system. Nevertheless, the role of electricity in recovery efforts following flooding merits consideration for future research. Farmers, for example, depend on electricity to engage in recovery activities aimed at restoring their farms and resuming production. This recovery process may involve employing electric pumps to drain floodwater from fields efficiently or utilising electric tools and machinery for necessary repairs. Therefore, access to electricity is critical in facilitating these recovery efforts. Insufficient and unreliable electric access can hinder and extend the time required for farmers to recover and regain full productivity, highlighting the intricate relationship between flooding, agriculture, and electricity systems within coastal communities.

4.5. The hazards of hotter days and nights

As climate change intensifies, coastal communities are increasingly experiencing elevated daytime and nighttime temperatures, leading to prolonged periods of extreme heat. Participant 5 from FGD7 noted her perspective on summer seasons: although the days and nights are hot, she does not view the temperatures as excessively high. In contrast, KI6 conveyed his deep concern about these rising temperatures, explaining, *"I often hear community members express their struggles with power outages during the summer, even in the absence of typhoons. These summers are particularly difficult for us; we face peak tourism season and receive numerous complaints about electricity and water shortages."*

These accounts present valuable insights into the correlation between increased temperatures during the day and night and the frequency of power outages, especially in the summer. This issue is further intensified by the peak tourism season, which places additional strain on the electricity supply [38]. Notably, however, our data indicates a deficiency in detailed insights from other participants regarding the implications of this phenomenon. Consequently, our understanding of the impact of elevated temperatures and frequent power interruptions remains inadequate. This gap underscores the pressing need for further examination of climate-induced temperature increases and their effects on electricity reliability in coastal communities, particularly during critical periods such as the summer [2,39].

5. Vulnerabilities associated with electricity sociotechnical systems

Coastal communities face significant threats from various hazards, and these detrimental impacts are intensified by the interaction of these hazards with existing vulnerabilities in the Calamianes Islands. As detailed in Section 2, we categorised these vulnerabilities into technical (5.1) and social (5.2) dimensions. From a technical perspective, we identified vulnerabilities associated with physical infrastructure and the management of electricity systems. Additionally, we examined the interdependencies between electricity systems and other critical infrastructures, including communication networks, water supply, transportation, and health facilities [2,60]. In the social dimension, vulnerabilities encompass socioeconomic factors such as low income, geographic location, access to essential lifeline systems, and barriers to information and communication.

5.1. Technical vulnerabilities

5.1.1. Physical infrastructure vulnerabilities

5.1.1.1. Exposure of the electricity system's physical assets. Extreme weather events pose a significant risk to transmission and distribution lines, resulting in considerable damage to overhead power lines [37]. This, in turn, leads to power outages, disrupting the availability and reliability of electricity [40,45]. FGD participants highlighted the severe effects of strong winds associated with typhoons. These winds can uproot trees, which subsequently fall onto power lines and posts, causing extensive damage [37]. Participant 5 from FGD9, shared, "*The strong winds uprooted trees that fell onto our electric lines and posts, seriously damaging our electricity infrastructure.*"

The study area displayed a disorganised installation of electrical components, rendering them vulnerable to weather-related hazards (see

(a) (b)

Fig. 3. (a) Electricity infrastructure supporting coastal homes, and (b) a ground-mounted transformer. Source: Eireka Orlido Meregillano, photographed in December and January 2023.

Fig. 3). This configuration significantly increases the risk of damage to these components. As illustrated in Fig. 3a, the substandard poles and inadequate boards for mounting electric meters and distribution lines exemplify these deficiencies. Such shortcomings make the system's physical elements susceptible to threats from extreme weather events and saltwater intrusion, especially in coastal regions. The elevated salt content in the atmosphere can severely degrade electrical components, including transformers, circuit breakers, and control systems [41]. This degradation compromises the equipment's structural integrity, increasing the likelihood of malfunctions or failures [42].

5.1.1.2. Ageing electricity infrastructures. Ageing electricity infrastructures refer to outdated and deteriorating electrical systems requiring substantial repairs or upgrades. As these infrastructures age, they increasingly exhibit unreliability, inefficiency, and a susceptibility to failures or disruptions [43,44]. This vulnerability gives rise to various risks, such as power outages, voltage fluctuations, safety hazards, and increased maintenance demands [44,45]. Participant 3 from FG8 expressed his concern poignantly: *"It feels like our electricity gets cut off far too easily, regardless of the weather. Sometimes it's as trivial as a gecko crawling on the lines or tree branches brushing against them. It's frustrating, especially considering how old these power lines are. We had a recent discussion with BISELCO, our local electric cooperative, along with a representative from the Department of Energy, regarding when they plan to address the outdated lines, particularly those in the mountainous areas, where the situation is considerably more challenging."*

5.1.2. Electricity system operations and management vulnerabilities

Vulnerabilities in operating and managing electricity systems refer to the inherent weaknesses or susceptibilities within these processes. These vulnerabilities primarily relate to the methodologies, protocols, and decision-making frameworks that underpin the system's effective and efficient functioning [46]. Consequently, such susceptibilities can significantly undermine grid reliability, stability, and resilience [45].

5.1.2.1. Workforce availability. The availability of a competent and sufficient workforce directly impacts the vulnerabilities associated with system operations and management in the electricity sector. This workforce comprises skilled personnel responsible for operating, maintaining, and managing various components of the electricity system, including power generation, transmission, distribution, and control.

Our data revealed significant delays and challenges the local electric cooperative faced in repairing damaged power lines and uprooted poles after typhoons. Notably, Typhoon Haiyan highlighted these issues, as Participant 2 from FGD4 shared, *"When a tree came crashing down and knocked out our electric wires, restoring normalcy took considerable time. It wasn't just my neighbourhood—almost everyone in Coron felt the impact. Even areas like Turda, Borac, and Buenavista, located much farther away, were severely affected. With only a few linemen available, working thinly spread, it took an age for our power to be restored."*

5.1.2.2. Interdependencies and cascading effects. The interdependencies of the electricity system with other critical infrastructures underscore the complex network of connections essential for the reliable delivery of fundamental services [45]. The effective functioning of the electricity system is intricately tied to various other critical infrastructures, such as water supply, communication, transportation, and healthcare facilities [2,47,60]. This relationship illustrates how disruptions in one area can significantly impact the operation of others, emphasising the need for a cohesive approach to infrastructure management.

A significant power outage can severely impair the ability of water treatment plants to provide clean water and disrupt transportation systems, thereby hindering emergency response efforts. Furthermore, breakdowns in other critical infrastructures, such as communication failures, obstruct the electricity system's capacity to coordinate emergency repairs and disseminate vital information effectively. Participant 4 from FGD8 expressed her concerns: *"I feel that our water supply in the barangay could be significantly improved. When it rains, we have a good water flow during the dry spells, but it struggles to meet our needs. Therefore, I believe we should invest in an electric water pump. Additionally, our water supply is adversely affected whenever there is a power outage, exacerbating our challenges."*

5.2. Social vulnerabilities

5.2.1. Low-income households

Low-income households consist of families or individuals who lack sufficient financial resources, with income levels falling below the poverty line or deemed inadequate to fulfil basic needs. Rural coastal communities have an average monthly income of approximately PhP 10,036.44 (~US$ 180). Consequently, these households face significant challenges due to their restricted access to alternative livelihood sources. As a result, they endure disproportionate and transformative effects from power outages, often caused by extreme weather events [61].

FGD participants from Busuanga articulated their financial constraints, which impede their capacity to implement preventive measures such as installing backup power systems or reinforcing their homes against severe weather conditions [48]. Consequently, they increasingly find themselves vulnerable to power outages and encounter difficulties in effectively managing prolonged disruptions to the electricity supply. For instance, Participants 2 and 4 from FGD8 expressed their challenges: *"As fishermen, we rely on this work for our livelihood, but it isn't a year-round job. This means we often struggle with inconsistent income, making it difficult to purchase larger solar-powered lights, which are quite expensive for our means."* This testimony highlights the critical need for targeted support and resources designed to enhance the resilience of low-income households in the face of climate-related disruptions [61].

5.2.2. Location and accessibility of lifeline systems

The location and accessibility of lifeline systems are crucial to the strategic placement and ease of access to essential infrastructure and services vital for a community's functioning and well-being, both in normal circumstances and during emergencies [48]. These systems highlight the importance of understanding how communities interact with their geographical environment to access essential lifeline services. For example, FGDs 1, 3, and 5 participants expressed that evacuation centres can be too distant for residents to reach effectively during crises. Furthermore, the accessibility of electricity transmission lines poses significant challenges, particularly in mountainous regions, where these lines can be difficult to reach and repair following typhoon events. In conversations with male informants, they underscored the urgency of addressing these accessibility issues (KIs 1, 3, and 5).

5.2.3. Geographic location

The susceptibility of barangays to various hazards underscores the critical importance of their geographic positioning. For example, barangays in low-lying coastal areas are particularly vulnerable to flooding, whereas those in mountainous regions face an increased risk of landslides. These geographic factors significantly contribute to the community's limited access to electricity. Participant 2 from FGD8 remarked, *"BISELCO, our local electric distributor, often struggles to provide reliable services to remote areas and island barangays."* This statement highlights the considerable challenges in delivering consistent electricity to these at-risk communities.

5.2.4. Information and communication barriers

Information and communication underscore the necessity of a robust communication infrastructure for effective emergency response, coordination, and the dissemination of vital information during extreme events, such as typhoons. However, participants expressed a pressing need for improved signal coverage for mobile phones. Participant 3 from

FGD6 articulated: *"It would be fantastic if we had our cell site! There are areas behind the mountain, where the barangays are, with no signal. We can't even reach them! We depend on radio communication in emergencies, especially when we must stay connected with the municipal disaster risk reduction team."* Her statement highlights the limitations of current communication systems, particularly in remote areas where connectivity is inadequate.

6. Risks associated with electricity sociotechnical systems in the Calamianes Islands

We found risks, including disruptions to the supply and distribution of electricity, communication disruptions, and economic losses.

6.1. Disruption of electricity supply and distribution

One of the most significant risks during a typhoon is disrupting the electricity supply and distribution [32]. The powerful winds associated with these storms can cause extensive damage to homes, electricity lines, and poles, especially in coastal areas where houses are often constructed with lightweight materials [31] (see Fig. 4a). Additionally, interview data revealed that electricity meters are frequently inadequately secured, rendering them vulnerable to being toppled by intense winds (see Fig. 4b). These strong winds also contribute to falling trees and flying debris, which pose substantial risks to both electricity infrastructure and human safety. Participant 1 from FGD2 vividly illustrated the consequences, remarking, *"Due to the fierce winds, many trees fell along with electric wires and poles."* Similarly, Participant 4 from FGD3 noted, *"The electric posts suffered significant damage."*

KI6 and KI7 reported that landslides have caused significant road blockages, exacerbating the challenges associated with rescue and relief operations and restoring and repairing damaged electricity infrastructure. Participant 4 from FGD4 expressed their concerns: *"After the typhoon, we as barangay leaders have found it difficult to clearly understand the damage in our community due to the numerous blocked roads. This predicament hampers our ability to assess the situation adequately and prolongs the arrival of outside assistance."* Similarly, K17 articulated, *"When landslides or debris obstruct the roads, repairing the damaged power lines and poles requires considerable time and effort. Consequently, we endure power outages that last longer than desired. It can be incredibly frustrating to be left in the dark due to these challenges."*

6.2. Disruption to communication

Communication disruptions significantly impair the coordination of emergency responses, undermining the capacity of emergency management agencies, first responders, and local authorities to share essential information. Such interruptions lead to delays in the deployment of resources, hinder rescue operations, and obstruct evacuation plans, ultimately endangering lives.

K17, a male official from the Municipal Disaster Risk and Reduction Office, highlighted the urgent need for robust communication strategies to facilitate a swift and coordinated emergency response. He stated, *"We are grappling with a power outage, which complicates our ability to communicate with nearby barangays. The absence of electricity makes it challenging to assess the impact on our community. We must connect with others to obtain real-time information; however, blocked roads due to landslides exacerbate this issue. The provincial government expects us to report on damages and needs promptly, but we risk delays in securing the necessary assistance without effective communication. Therefore, we must establish an alternative communication method after the typhoon, ensuring we can inform the province immediately. This approach will prevent us from falling behind in our efforts to receive support."*

Effective communication between rescuers and distressed individuals is crucial for successful search and rescue operations. Disruptions to this communication can severely hinder the coordination of efforts, impede the ability to locate and respond to distress signals, and ultimately compromise the safety and well-being of those in need. Moreover, K17 underscored that communication barriers prolong response times and may exacerbate the situation for those requiring assistance. K17 expressed, *"We struggle to understand how power outages impact our communities, or barangays. When the lights go out, we must*

(a) (b)

Fig. 4. (a) Homes of informal settlers and (b) power lines situated along the Busuanga coast. Source: Eireka Orlido Meregillano, photographed December 2023.

quickly assess the damage and identify what people need. This requires gathering information immediately and determining how many assessments are necessary to understand the situation clearly. However, effective communication is essential during these challenging times, as it allows us to share accurate updates promptly."

Effective communication channels are essential in bolstering community resilience. Disruptions to these channels can significantly impair a community's ability to unite, share information, and offer mutual support before, during, and after extreme weather events. For instance, Participant 3 from FGD8 shared, *"Reaching out to my family and the authorities proved challenging. We struggled with confusion about our next steps. When the typhoon struck, I had to find higher ground to improve my cell phone signal. Sadly, after Typhoon Yolanda, all the communication towers were down."* Additionally, KI6 expressed tourist concerns about communication during typhoons, stating, *"I hear they find it incredibly difficult to get in touch with their loved ones back home, which highlights the urgent need for reliable communication methods during such storms."*

Coastal communities must establish comprehensive and redundant communication systems to effectively mitigate the adverse impacts of communication disruptions during extreme weather events. These systems should include backup power sources and alternative communication methods, such as battery-operated or rechargeable handheld two-way devices. Furthermore, community alert systems and public education initiatives must inform individuals about available communication options and emergency protocols. It is imperative that communities actively engage in these practices to enhance resilience against severe weather conditions.

Collaboration and coordination among government agencies, telecommunications providers, and community organisations are essential for strengthening communication resilience. Such joint efforts enhance the safety and well-being of coastal communities and facilitate a proactive response to the challenges posed by extreme weather conditions. Prioritising these strategies will enable coastal areas to significantly improve their preparedness and response capabilities, safeguarding their inhabitants during crises.

6.3. Economic losses

Economic losses refer to the financial burdens that arise from damage, disruptions, or adverse repercussions within various economic sectors. For instance, power outages significantly impede manufacturing processes, leading to production shortfalls, supply chain disruptions, and financial setbacks for businesses. In the sites studied, the primary sources of income include fishing, agriculture, and tourism [49]. These economic losses have consequences that extend to the community level, resulting in job displacements, slowed economic growth, and a diminished quality of life.

K11 recounted their experience: *"In 2022, Typhoon Paeng struck our community, causing immense distress. The severe flooding compelled us to declare a state of calamity; the airport was submerged, and a landslide obstructed the road leading to this crucial transport hub."* The suspension of flights profoundly impacts the local economy, particularly within the tourism sector and for small businesses. This incident initiates a cascading effect across multiple sectors; specifically, flight cancellations lead to a direct decrease in the influx of tourists, which, in turn, causes financial losses for resorts and other local enterprises.

The disruption of livelihoods in coastal communities exacerbates economic instability, as the affected individuals often face significant changes in their occupations [50]. Fishing, a crucial source of income for many residents in these areas, becomes severely compromised during extreme weather events like typhoons, rendering it impossible for fishermen to venture out to sea. For instance, KI2 vividly articulated the profound effects of these storms, *saying, "The impact of a typhoon is felt both before and after it passes. Even before a storm arrives, when PAGASA (the Philippine weather service) issues gale warnings, the strong winds and high waves make it far too dangerous for us to go to sea." Similarly,* Participant 3 from FGD8 shared their struggles during such challenging times, reflecting, *"Our livelihoods suffered immensely during that period. Although my husband tried to supplement our income by selling ice cream, we lost electricity, which made ice cream production incredibly difficult. As a result, we had to adapt by sourcing tube ice from Coron to satisfy the demand for cold water when local supplies dwindled."*

Other livelihoods dependent on tourism and electricity were significantly affected. A woman Participant 4 from FGD3 shared her experience, stating, *"After Typhoon Yolanda struck, my small store struggled tremendously due to prolonged power outages. We depend on maintaining the right conditions for our cold cuts and frozen foods in the fridge and freezer, which posed a serious problem when the electricity failed. Without power, we could not preserve our products at the proper temperatures, leading to spoilage and waste. Witnessing our inventory deteriorate was heartbreaking and had a severe financial impact. Furthermore, the entire month-long wait for the power to be restored exacerbated the challenges we faced in running our business."*

In developing countries such as the Philippines, extreme weather events severely impact livelihoods due to limited resources and inadequate adaptive capacity [50,61]. Moreover, various social vulnerability factors, including poverty and disability, significantly hinder coastal community capacity to respond effectively to these challenges. Hence, addressing these issues is crucial for enhancing resilience in these regions.

7. Discussion

7.1. Vulnerability of coastal communities to climatic hazards

Coastal communities exhibit heightened vulnerability to climatic hazards, including typhoons, storm surges, intense rainfall, and flooding [8,4,51]. These hazards directly threaten electricity systems, adversely impacting power plants, substations, transmission lines, and distribution networks. The significant exposure of coastal communities to such climatic phenomena markedly increases the risk of infrastructure damage, resulting in severe disruptions to the power supply. This relationship between environmental hazards and energy provision underscores the urgent need for resilient strategies to safeguard essential services in these areas. Moreover, the proximity of coastal infrastructure to the ocean exacerbates vulnerability due to ongoing exposure to saltwater, strong winds, and various coastal conditions. The corrosion of power lines and substations from saltwater significantly undermines their structural integrity [42]. Consequently, the compromised state of energy infrastructure intensifies the risks associated with climatic hazards, necessitating systematic assessments and targeted interventions.

7.2. Cascading effects of electricity disruptions

Disruptions to the electricity system caused by climatic hazards can lead to extensive and cascading effects on coastal communities. Power outages interrupt essential services, such as water supply, communication networks, healthcare facilities, and emergency response [47,60]. This interdependency among services increases the risks and vulnerabilities faced by the electricity system, posing significant challenges to the broader community and amplifying the threats posed by climatic hazards. Such dynamic interrelations underscore the pressing need for strategies to enhance resilience in these vulnerable coastal areas. To effectively address these cascading effects, a multi-faceted approach is required, to acknowledge the interconnectedness of various community services and promote a more integrated disaster response framework.

7.3. Socioeconomic vulnerabilities and their impact

Socioeconomic vulnerabilities significantly exacerbate the risks faced by electricity systems in coastal communities, closely intertwining with the climatic hazards these areas endure. Such vulnerabilities are particularly pronounced among low-income households (cf. [61]), which are characterised by limited access to essential resources, inadequate infrastructure, and a reliance on specific industries, including fishing and tourism.

Consequently, these socioeconomic factors intensify the impacts of climate-related hazards on the electricity sector, complicating recovery from disruptions. This interplay highlights the urgent need for a holistic approach to strengthen resilience within these communities. Furthermore, strategies to improve socioeconomic conditions, such as creating jobs and providing access to affordable energy solutions, can effectively mitigate the adverse effects of climatic events and enhance community resilience.

7.4. Strengthening electricity services and local governance

BISELCO, the local electricity provider, operates as a monopoly and currently suffers from understaffing, which impedes its ability to deliver reliable services. Although increased revenue is needed to improve operations, residents often express dissatisfaction due to the high electricity costs. To resolve this issue, the local government could introduce subsidies to alleviate the electricity provider's operational costs. This financial support would facilitate service enhancements without imposing additional burdens on consumers.

Ultimately, fostering competition within the market by inviting more electricity providers could lead to improved service quality and reduced prices for consumers [52]. Furthermore, proactive measures should be adopted to enhance the resilience of the electricity infrastructure during the off-season. These measures may include removing branches and trees from power lines, strategically positioning electrical transformers, and using more durable materials for electrical posts capable of withstanding severe typhoon winds.

Local government units are critical in disaster response, often acting as the first line of defence during emergencies [53]. Effective local planning and budget allocations are essential to ensure these entities can adequately address crises. Reliable communication equipment is vital for first responders; it enables them to maintain situational awareness, coordinate rescue efforts, and manage transportation and other operations effectively.

Additionally, enhancing communication with community members through affordable and accessible mass media channels is equally essential (cf. [54]). This study demonstrates that public service announcements delivered via the Internet and mobile telecommunications networks can be highly effective. Since hazards often have seasonal patterns, planning and resource allocation must occur well in advance, allowing local governments to adequately prepare to mitigate risks and respond swiftly when disasters arise [53].

7.5. Potential solutions and policy implications: integrating risks and sustainability for enhancing sociotechnical electricity system resilience

Addressing the challenges of sociotechnical electricity systems in typhoon-prone coastal communities necessitates considering potential solutions and policy implications. These systems are inherently complex, intertwining technological components with social factors. The primary objective is to ensure the safety, well-being, and long-term economic stability of these coastal communities. Consequently, enhancing the resilience of electricity infrastructure, particularly during extreme weather events such as typhoons, is essential. This approach requires viewing the situation sociotechnically, fostering collaboration, and prioritising community engagement to achieve effective outcomes.

It is crucial to recognise the importance of assessing risk. Evaluating the various types of risk within the energy system is fundamental to ensuring energy security [10]. Although risk is central in this context, it is often inadequately defined or employed informally concerning energy security [55]. It is crucial to distinguish risks from vulnerabilities: risks refer to adverse consequences, whereas vulnerabilities denote the inability to manage them. Coastal communities encounter environmental hazards such as typhoons, representing external threats that are challenging to mitigate. These threats exacerbate existing vulnerabilities, including socioeconomic disparities and ineffective communication networks.

Solutions and policies must consider various risks pertinent to electricity systems, including supply chain and systemic risks [56]. Supply chain risks significantly impact energy systems, exemplified by disruptions in obtaining materials necessary for repairs or operations following a typhoon. Additionally, systemic risk pertains to the potential for disruptions to propagate throughout the interconnected system [47]. Notably, these critical risk features remain under-researched in the literature on energy security.

A broader characterisation of risk is essential for complex systems such as coastal electricity grids, especially in the aftermath of a disaster. This can be achieved by employing scenarios to qualitatively understand impacts, as reliance solely on probability distributions may prove inadequate. Moreover, methodical and transparent risk assessment, acknowledging knowledge and knowledge gaps, is crucial, particularly when risks are challenging to quantify. Furthermore, insights drawn from sustainability assessment procedures could substantially enhance energy security analysis. Achieving a balance between risk and sustainability is vital in energy security.

Policies designed to enhance resilience should consider the diverse sociotechnical imaginaries held by various stakeholders, including government entities, community members, and other influential actors [17]. While dominant imaginaries frequently guide policy decisions, recognising alternative imaginaries is crucial [17]. Engagement and collaboration with the community are vital for strengthening the robustness and resilience of infrastructure. Furthermore, such initiatives can signify the emergence of alternative imaginaries, which may arise from a grassroots perspective or through prefigurative activism [17].

The influence of sociotechnical imaginaries on policies, practices, research directions, and resource mobilisation illustrates their performativity [17]. Moreover, policies and strategies can be regarded as public representations of these imaginaries. Consequently, the formulation of policies aimed at developing resilient coastal electricity systems is informed not only by technical requirements and risk assessments but also by the shared visions of what these communities and their energy systems should aspire to in the future.

The policy implications are complex and require careful consideration. It is crucial to recognise that underlying sociotechnical imaginaries significantly influence policies; thus, articulating these visions explicitly can enhance the formulation and implementation of policies [17]. Furthermore, policies aimed at bolstering resilience must account for the diverse imaginaries present within affected communities and among stakeholders, including alternative visions that emerge from local needs and capacities [17].

Adopting robust, systematic, and transparent approaches to risk assessment is essential, moving beyond informal methods to explicitly incorporate uncertainties and ambiguities [56,57]. Additionally, forthcoming policies must address supply chain risks and the systemic risks inherent in interconnected electricity systems, as these risks can result in severe consequences [47]. Lastly, a holistic understanding of the temporal dimensions embedded within various imaginaries—namely, the timeframes envisioned by different actors for the system—can significantly inform policy timelines and long-term planning strategies [58].

8. Conclusion

8.1. Summary of findings

This study investigates the hazards, vulnerabilities, and risks associated with sociotechnical electricity systems in typhoon-prone coastal communities of the Calamianes Islands, Philippines. Our findings reveal that these coastal communities face significant challenges from environmental hazards and systemic vulnerabilities. Additionally, these interconnected issues exacerbate the overall risks to local communities and their electricity infrastructure.

Climatic hazards, especially the prevalence of severe typhoons, trigger cascading effects such as storm surges, landslides, strong winds, and flooding [51]. These effects directly impact the electricity infrastructure. Furthermore, these hazards interact with existing vulnerabilities, which can be categorised into technical and social dimensions. Technical vulnerabilities make aged electricity infrastructure more susceptible to failure and disruption, heightening risks such as power outages and voltage fluctuations. Additionally, social vulnerabilities, including accessibility difficulties that hinder disaster response and communication barriers that obstruct the dissemination of information, significantly limit community capacity to prepare for and respond to such events.

The interaction between hazards and vulnerabilities generates critical risks for sociotechnical electricity systems. These risks include disruptions to electricity supply and distribution, cascading effects across interlinked systems, and compounded impacts arising from deteriorating infrastructure and social factors. The findings emphasise that enhancing community safety, well-being, and long-term economic stability necessitates improving the resilience of these complex sociotechnical systems. This enhancement involves addressing technical deficiencies and strengthening social capacities, all while recognising the interconnections between technological components and social factors within the system [48].

8.2. Study limitations

This study employed a qualitative methodology comprising interviews and FGDs. While these methods provided valuable insights into electricity HVRs in typhoon-prone coastal communities, they are not without limitations. Notably, there was a gender imbalance among key informants, particularly concerning the underrepresentation of women's perspectives. This disparity may reflect broader societal trends in the Philippines; however, it has the potential to limit the scope of insights related to infrastructure resilience and electricity access. Therefore, future research should strive for a more balanced participant composition to enhance the diversity of viewpoints.

This research examines the coastal communities of Busuanga, Coron, and Culion Islands in the Calamianes to capture their diverse needs. However, it does not provide a comprehensive analysis of all coastal communities in the archipelago. A more detailed evaluation of the engineering and financial aspects of the electricity technologies would have been beneficial, requiring expertise beyond the current study's focus (see [59]).

Moreover, the study identified several key risks associated with the electricity sociotechnical system. However, a systematic and transparent assessment of various risk types—particularly less visible risks such as supply chain issues (e.g., logistics of post-typhoon repair materials) and systemic risks (e.g., the propagation of failures across interconnected infrastructures and social systems)—poses significant challenges for qualitative methods. Furthermore, addressing the uncertainties and ambiguities inherent in complex systems and unpredictable events, such as typhoons, is challenging without the implementation of structured risk analysis methodologies.

8.3. Opportunities for future research

This study provides a foundational understanding of the challenges faced by sociotechnical electricity systems in typhoon-prone coastal communities and identifies several promising avenues for future research. Acknowledging the limitations of the current work, future research should rigorously investigate the complex interplay among technology, society, risk, sustainability, and the collectively envisioned futures of these systems.

Future research must thoroughly investigate the sociotechnical imaginaries associated with electricity and resilience in coastal communities. This inquiry should focus on the dominant imaginaries articulated by government agencies, utility companies, and other key stakeholders and the alternative imaginaries presented by community members, local leaders, and NGOs. Understanding the emergence, stabilisation, contestation, and interaction of these imaginaries within policies, investments, practices, and everyday life is crucial. Appropriate methodologies may involve analysing policy documents, media sources, stakeholder discourse, and conducting ethnographic fieldwork to capture the manifestation of imaginaries in daily practices. Additionally, examining the temporal dimensions of these imaginaries, particularly the future timeframes envisioned by various actors, could provide valuable insights for long-term planning.

Future research must progress towards more robust, methodical, and transparent analyses of the various risks coastal electricity infrastructure faces, particularly in extreme weather events. To achieve this, it is essential to develop frameworks that clearly define and categorise these risks. Systemic risks require specific attention, encompassing cascading failures among interdependent infrastructures, such as power, communication, and transport, and the societal systems that depend upon them.

Furthermore, investigating supply chain risks related to repair and recovery logistics following disasters is crucial, as these aspects are currently under-researched yet vital features of the infrastructure landscape. Research should also explore scenario-based methodologies to qualitatively assess the impacts of risks that are challenging to quantify using probabilistic methods. In addition, comparative studies examining different energy vectors, such as centralised grids versus distributed renewable systems, are warranted to provide a comprehensive understanding of risks across varying contexts.

Further research should examine how concepts and methods from sustainability assessment can be integrated to enhance the analysis of energy security and system resilience in vulnerable regions. This undertaking necessitates the development of frameworks that ensure methodological transparency and comprehensiveness while capturing socioecological impacts at various scales. Additionally, research could explore strategies for reconciling the often short-term focus of energy security concerns with the long-term environmental and social sustainability objectives in policy and planning. Understanding how sociotechnical imaginaries shape the interplay between resilience, energy security, and sustainability may reveal pathways towards achieving desirable energy futures. Finally, investigating the role of diverse stakeholder engagement is crucial in building resilient and sustainable energy systems that reflect a variety of imaginaries and risk perceptions, thereby informing effective policy and action.

Research opportunities are crucial in enhancing the adaptation and sustainability of electricity sociotechnical systems in coastal communities. Exploring these avenues allows researchers to develop effective strategies for constructing resilient energy systems that endure extreme weather events and foster these communities' overall well-being and prosperity.

CRediT authorship contribution statement

Eireka Orlido Meregillano: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Laurence L. Delina:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1. Key informant interview guide

Introduction

We cordially invite you to engage in our research study "Understanding the Complexities, Intersectionality, and Multidimensionality of Energy Fragility in the Coastal Communities of Busuanga Islands, the Philippines." This study aims to identify the economic, social, and ecological factors influencing the energy resilience of coastal communities vulnerable to extreme weather events and examine how households adapt to these challenges. An in-person interview will be conducted with you. While we will report your locations in our findings, we will keep your name confidential. Your anonymity is a priority. We will collect data on: (1) demographic, social, economic, and environmental threats to your electricity system; (2) your coping mechanisms and adaptive strategies during extreme weather; and (3) your proposed solutions and approaches for enhancing energy resilience. Thank you for your valuable participation in this important research.

Guide questions

- Please share some details about yourself and your organisation.
- What extreme weather events are prevalent on the island? What particular hazards (e.g., typhoons, prolonged dry spells, floods) have you observed concerning your electricity access during these weather extremes? Please share any experiences you have had.
- What are the impacts or implications of typhoons on the energy supply in your community? You may discuss these impacts in terms of their technical, social, financial, political, economic, environmental, and cultural dimensions. What about during prolonged dry spells?
- How reliable is your electricity connection, meaning zero interruption and no blackouts, during extreme weather events? Please share any experiences you have had. How do these interruptions affect your daily work and livelihood?
- Who are the most impacted by these hazards? What are the different effects on children, women, low-income households, and persons with disabilities? How do they cope?
- What programs, projects, or activities are in place to address the impacts of extreme weather events on your electricity systems? What do you think of these?
- How can alternative energy sources, like diesel generators and solar panels, assist you during electricity disruptions? How can you access these alternatives? What prevents you from accessing them?
- What are your suggestions for improving your coping strategies during typhoons or prolonged dry spells?
- How has your electricity supply changed in the last ten years? What improvements would you like to see, particularly in mitigating and absorbing the risks, hazards, and vulnerabilities of extreme weather events?

Ending questions

- How do you define energy resilience?
- Do you have anything else to add?

Closing

It is the end of our interview. Thank you very much for your participation. Again, the research team will be happy to discuss any concerns you may have about your involvement in this project. You can contact them to obtain information about the study results.

Appendix 2. Focus group discussion guide

Introduction

Good day! We invite you to participate in this research entitled "Understanding the Complexities, Intersectionality, and Multidimensionality of Energy Fragility in the Coastal Communities of Busuanga Islands, the Philippines." *Magandang araw! Inaanyayahan namin kayong makilahok sa pag-aaral patungkol sa katatagan ng kuryente sa pamayanang dagat sa mga isla ng Busuanga.*

This study seeks to determine the economic, social, and ecological factors that affect energy resilience of coastal communities due to extreme weather conditions and analyze how households respond to these challenges. We will conduct an in-person interview with you. We will identify your locations in our reports and outputs but not your name. You will remain anonymous. We will gather data on (1) demographic, social, economic, and environmental threats to your electricity system, (2) your coping mechanisms and your adaptive strategies at times of weather extremes, and (3) your solutions and approaches to increase your energy resilience. *Sinisikap ng pag-aaral na ito na malaman ang mga iba't-ibang kadahilanang nakaapekto sa katatagan ng kuryente sa inyong mga pamayanan. Pag-aaralan din ang epekto ng kondisyon ng panahon at ang mga naging sagot ng inyong pamayanan sa mga nasabing problemang inyong kinakaharap. Magkakaroon tayo ng interbyu. Ilalathala ang inyong mga pamayanan pero hindi* namin *ilalabas ang inyong mga pangalan. Aalamin namin mula sa inyo ang mga sumusunod: (1) Mga bagay na nakaaapekto sa inyong pagkakaroon ng maasahang kuryente, (2) ang inyong mga naging sagot sa mga problemang kinakaharap ng inyong supply ng kuryente; at (3) ang inyong mga mungkahi para maging mas matatag ang inyong supply ng kuryente dito sa inyong pamayanan.*

The discussion will take up to 90 min of your time. Some questions may cause minimal discomfort since we want to know about your personal experiences. Please be advised that you are under no obligation to engage in this interview if you think it will result in any emotional distress on your part. Suppose you still chose to participate and felt upset after the discussion or found some questions or aspects of the study triggered distress. In that case, we will provide you with information on where to access mental health and psychological support services and assure you of the confidentiality of acquiring such services. *Aabot ng isa't kalahating oras ang interbyu. Ganun din po, ang diskusyong ito ay amin pong irerekord para lang po sa kadahilanang makuha po namin lahat ang inyong mga sagot sa mga tanong. Iilan sa mga tanong ay aalamin ang inyong mga personal na karanasan. Dapat ninyong mabatid na pwedeng hindi kayo sumama sa interbyu na ito, kung sa tingin ninyo ay masyadong personal na ang mga tanong sa interbyu. Kung kayo man ay naapektuhan sa pagtatanong ng personal, maari naming alisin na lang ang inyong mga sagot o partisipasyon sa interbyu.*

We cannot promise that you will receive any other benefits from this study besides access to published outputs, which you can request anytime. *Hindi kami nangangako ng pabuya ngunit makatitiyak kayo na kapag natapos ang pag-aaral na ito, ay pwedeng pwede kayong makahingi ng kopya nito.*

This discussion is entirely voluntary. There is no need to take part unless you wish to do so. If you decide not to participate, you can withdraw at any stage and ask for all information provided to be returned to you or destroyed. However, once the data analysis has begun, it will become increasingly difficult to remove the influence of your data on the results. *Ang interbyu na ito ay kusang loob at hindi sapilitan. Maari kayong hindi sumama sa interbyu kung nais niyo. Kung nais niyong hindi sumama sa interbyu, maari kayong umatras sa anumang panahon at ang impormasyon ninyo ay ibabalik at hindi isasama.*

The information you provide will remain strictly confidential. Only the research team will have access to the information you provide in the discussion. The paper and audio data are stored for at least seven years in a secure and password-protected computer at the university and then disposed of by deleting and shredding as part of the university's ethical requirements. Any information obtained from this study will remain confidential and be disclosed only with your permission or as required by law. If you consent to participate, we have planned that the results will be published in journal articles or books and reported at conferences or meetings. *Ang mga impormasyon na aming makakalap mula sa inyo ay kompidensyal. Tanging ang aming research team lamang ang may hawak o may akses sa lahat ng impormasyong ito.*

The research team will be pleased to discuss any concerns about your participation in this project. You can contact them if you wish to obtain information about the result of the study. *Kung kayo ay may iba pang katanungan tungkol sa pagaaral na ito, maaari nyo po kaming sulatan o tawagan.*

Opening question/Ice breaker

Could everyone start by introducing themselves – e.g., your age, and occupation, and how long have you been living here in your community? *Maari bang magpakilala ang bawat isa? Pakilahad ang inyong edad, ang bilang ng taon kung gaano na kayo katagal sa pamayanang ito, ano po ang ating kabuhayan o okupasyon, at ilang taon na po tayo sa ating kabuhayan o okupasyon? Magsisimula po ako.*

Introductory question

How would you describe your community? What are your strengths as a community? *Pakilarawan ang inyong komunidad. Ano sa tingin ninyo ang kalakasan ng inyong komunidad? Ano naman sa tingin Ninyo ang kahinaan ng inyong komunidad?*

Transition question

What do you think are the benefits of electricity in your life*? Anu-ano sa tingin Ninyo ang benepisyo o tulong ng kuryente sa inyong buhay?*

Key questions

How do you get access to electricity? If you are not grid-connected, why you do not have electricity access, and how do you meet your electrification needs. If yes, tell me the process to connect to the grid, who are involved, and the challenges you encountered. *Saan kayo nakakukuha ng inyong kuryenteng ginagamit sa araw-araw? Mayroon ba ritong hindi konektado ang kuryente sa BISELCO? Maari niyo po bang ipaliwanag kung bakit hindi kayo konektado sa BISELCO? Natutugunan niyo rin ba ang inyong pangaraw-araw na pangangailangan sa kuryente kahit hindi kayo konektado sa BISELCO? Sa mga nakakabit ng linya sa BISELCO, maari niyo bang ipaliwanag ang mga hakbang sa pagpapakabit sa BISELCO, at kung ano ang mga naging balakid kung mayroon man?*

Meanwhile, what challenges do you face regarding electricity from the past (say, the 1980s) to today? *Mula sa inyong karanasan, ano ang mga napapansin ninyong naging problema sa pagkakaroon ng kuryenteng maasahan sa lahat ng oras at panahon?*

How reliable, meaning, zero interruption/no blackouts, is your electricity connection? What do you think are the reasons for these interruptions? How long does the interruption usually last? How do these interruptions affect your daily work? *Nagkakaroon ba ng mga black out sa inyong komunidad? Ano sa tingin ninyo ang mga dahilan ng pagkakaroon ng black out? Gaano katagal ang karaniwang black out? Paano nakaaapekto ang mga black out sa inyong pang-araw-araw na buhay?*

How affordable is your electricity? Please comment on your (monthly) electricity expenses (regardless of whether it is grid-connected or not) relative to your (monthly) income? *Mahal, mura, o katamtaman ba ang sinisingil sa kuryente? Ano ang inyong masasabi sa bayarin Ninyo sa kuryente kada buwan? Aabot ba ang bayarin sa kuryente ng sampung porsyento ng inyong kinikita kada buwan?*

What are the hazards of typhoons and long dry spell to your household? How about to your community/barangay? *Anu-ano ang mga panganib na dala ng mga kalamidad gaya ng bagyo, pagbaha, storm surge, mas mainit na mga araw at gabi sa inyong kabahayan o komunidad?*

Who are the most impacted by these hazards? What are the different impacts to children? To women? To low- income households? To persons with disability? How do they cope? *Anong bahagi ng inyong pamayanan ang pinakaapektado sa pagkawala ng daloy ng kuryente dulot ng bagyo?*

How do you personally (or your household) cope with the hazards you mentioned? *Sinu-sino ang sa tingin ninyo ang pinakaimportante na makakatulong sa inyo sa pagharap sa mga panganib na dulot ng mga kalamidad? Anu-ano ang inyong ginagawang sagot sa inyong mga kinahaharap na panganib dulot ng mga kalamidad sa daloy ng inyong kuryente?*

How does a typhoon affect your electricity access? Please tell me any experience you have? How about during a long dry spell? Please share your experience too. *May epekto o impluwensya ba ang mga bagyo o kalamidad sa daloy ng kuryente sa inyong komunidad? Paano nakakaapekto ang bagyo sa daloy ng inyong kuryente? Maaari nyo bang ibahagi o ikwento ang inyong karanasan tungkol sa epekto ng bagyo sa daloy ng kuryente? Paano naman po sa ibang pang kalamidad na dulot ng bagyo gaya ng pagbaha o storm surge? Maari nyo po ba itong ikwento sa amin?*

What particular hazards had you observe these weather extremes to your access to electricity? *Anu-anong mga panganib ang inyong mga naobserba na dulot ng mga bagyo at iba pang kalamidad sa daloy ng inyong kuryente?*

How does your electricity supply change in the last 10 years? What would you like to see improved? *Anu-ano ang inyong mga nakitang pagbabago sa daloy ng inyong kuryente sa loob ng 10 or mahigit ng taon? Anu-ano ang nais nyo pang maging pagbabago sa daloy ng inyong kuryente?*

Short break for refreshments

How do your barangay officials and LGUs assist you before, during, and after a typhoon? A long dry spell? Who else do you ask for help during typhoons or long dry spells? *Sa paanong paraan kayo natutulungan ng mga opisyales sa barangay o munisipyo bago, habang at pagkatapos dumaan ang isang bagyo o kalamidad?*

How do you prepare for electric disruptions due to typhoons or long dry spell? How do you cope after? *Paano kayo naghahanda sa pagkawala ng kuryente kung ito ay naapektuhan ng mga kalamidad mula sa panahon? Ano ang inyong mga ginagawa matapos kayong madaanan ng isang kalamidad?*

How could alternative sources of energy, such as diesel generators, solar panels, assist you during electricity disruption? How could you access these alternatives? What impedes you from accessing them? *Pwede kayang maging solusyon ang mga alternatibong pinagkukunan ng enerhiya tulad ng diesel generator o solar panel sa panahong may black out? May paraan ba kayo para makagamit ng diesel generator o solar panel? Ano ang mga balakid sa paggamit Ninyo ng mga alternatibong pagkukunan ng kuryente?*

What does your government provide your community to help them "bounce-back" from disasters? What help does the government give in ensuring reliable electricity connection? Aside from the government, are there any organisations that help the community in getting reliable electric connection? *Anu-anong mga hakbang ang ginagawa ng inyong munisipyo para matulungan ang inyong komunidad upang makabangon-muli mula sa isang kalamidad kagaya ng bagyo? Anu-anong mga hakbang naman ang binibigay ng inyong munisipyo upang masiguro na meron kayong sapat at maasahang daloy ng kuryente bago, habang, at pagkatapos ng isang kalamidad? Maliban po sa ating munisipyo, meron po bang ibang organisasyon na tumutulong sa inyo upang matulungan ang inyong komunidad upang mapanatiling tuloy-tuloy ang daloy ng kuryente sa panahon ng kalamidad gaya ng bagyo? Ano ang inyong solusyon o rekomendasyon sa pagkawala ng daloy ng kuryente na dulot ng bagyo at iba pang kalamidad? Sa inyong palagay, paano kaya mapapabuti ng inyong munisipyo ang pagpapanatiling tuluy-tuloy ang daloy ng kuryente sa panahon ng kalamidad gaya ng bagyo? Sa inyong palagay, paano kaya mapapabuti ng BISELCO ang kanilang serbisyo?*

Ending question

How do you define energy resilience? *Para sa inyo, ano ang ibig sabihin ng katatagan sa kuryente?*

Closing

This concludes our discussion. Thank you very much for your participation. Again, the research team will be pleased to address any concerns you may have regarding this project. You can also contact them to obtain information about the study results.

Data availability

Data will be made available on request.

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