Published by :
https://www.ijert.org/
An International Peer-Reviewed Journal

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 03 , March - 2026

Mitigating Power Outages through Flood-Resilient Distribution Systems: Strengthening Energy Resiliency in Plaridel, Bulacan

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Abstract - Flooding has become an issue of significant concern to stability of electrical distribution system in low-lying regions in the Philippines especially in municipalities prone to flooding such as Plaridel, Bulacan. As a result, frequent flooding during the monsoon seasons and other weather hazards have led to frequent breakdown of power and equipment that leads to a long time disruption of services, which in turn has impacted negatively on the safety of people and economic activities. Hence, this paper examines the flood-related vulnerability of the local electrical distribution system of the municipality of Plaridel and explores the usefulness of flood-resistant mitigation measures in accordance with the Philippine Energy Plan (PEP) 2023 2050. A descriptive-analytical research approach was used, which combined the municipal flood records and the fragility-based failure probability modeling and Monte Carlo simulation in order to understand the performance of major components of the distribution in different flood conditions. To determine the probability of failure of distribution transformers and switch gears as a function of flood depth, logistic fragility curves were constructed. Reliability indices such as probability of failure, outage time and mean time to repair were used to compare baseline system performance with proposed mitigation designs using elevated transformers and waterproof switch gears. A cost-benefit analysis was also done to determine the cost-effectiveness of the intended mitigation measures. The simulation results show that the current distribution system has high chances of failure when the flood depth is beyond 1.52.0 m, which is in line with the recorded flood condition in Plaridel. The mitigation strategies proposed greatly minimize the chances of component failure, system downtime, and restoration time, and the mitigation strategy combined has a reduction of over 80 percent in the risk of failure. Economic analysis shows that the loss saved due to outage is more than the initial capital investment resulting in a payback period of about 3-5 years. The results affirm that the advantages of flood resilient designs of distribution system are both technical and economic in nature and thus offer a feasible avenue of enhancing the energy resiliency of the flood prone communities.

Keywords: Flood resilience, electrical distribution systems, power outages, fragility modeling, Philippine Energy Plan 2023-2050, Monte Carlo simulation

I. INTRODUCTION

As an archipelago that is situated in a location that makes it highly vulnerable to extensive rainfalls and/or typhoons, power outages (due to this reason) has become a common occurrence in the Philippines. Among them, the Province of Bulacan is one of the most flood-prone provinces across Philippine geography. Specifically, Plaridel is one of those municipalities under the latter province that is constantly exposed to recurrent flooding due to it being geographically located in a low-lying area and being situated alongside the Angat River. As a result, the electric distribution systems (transformers, utility poles, feeder lines) were commonly affected, to which subsequently leads to power outages that disrupts major services and impacts the households present in the area [1].

According to a planning material specifically developed for the municipality of Plaridel which comprises the existing local vulnerabilities of the said area, flood hazards are usually present during the climate-induced typhoons, which significantly affects the operational power lines of the municipality [2].

In order to prevent an even greater potential impact of these outages especially during the time of calamities, the Department of Energy (DOE) formulated the Philippine Energy Plan (PEP) 2023-2050 which specifically highlights the importance and necessity to improve the resilience of every energy infrastructure and facilities in the Philippines by investing in various mitigation strategies that conforms with the latter goal. Various collaborations were also constantly being made and developed in order to secure funds for this specific plan.

Due to the electric distribution systems of the municipality of Plaridel, Bulacan that are highly susceptible to any damages especially during on climate-induced floodings, it is highly imperative to address the latter by introducing specific distribution systems that can withstand flooding. This will be done in order to mitigate, if not totally eradicate, the frequent power outages within the said location that will ultimately strengthen the overall resiliency of the municipality especially in the near future.

To achieve this, the effects of the climate caused flooding on the already established power distribution systems in the municipality of Plaridel, Bulacan have to be first identified and analyzed through the available data, the past history, and technical reports. This also includes a review at historical records of flooding, its frequency, depth, and duration, and the level of damage that it has inflicted to the electrical infrastructure including substations, transformers, and distribution lines. Using these data and interpreting them, the study will be capable of determining the weak points of the existing distribution network and what points are the most vulnerable to disruption caused by floods. The process will provide an opportunity to test and work out appropriate designs and configurations of the electric distribution systems that would meet the flood-resilient principles. Such suggested systems will be then compared with the current arrangement in the municipality to understand how viable, effective and capable of improving the resiliency of the situation in the long term such suggested systems are.

In order to have an all inclusive and holistic study, the proposed study shall majorly rely on the proposal of flood resistant distribution systems that will serve the municipality of Plaridel, Bulacan greatly in the light of rising climate risks and extreme weather conditions. The solutions that are proposed are meant to reduce power outages and improve the continuity of electricity services during and after the occurrence of floods. Particularly, the waterproof switch gears, elevated transformers and sealed cable connection will be given much focus as they are major elements that can endure exposure to water and avoid short circuiting or destruction. The use of new monitoring technologies and high substation design to make resiliency even better will also be examined in the study. In general, it is hoped that the proposed flood-resilient distribution systems can be used as a road map to sustainable and ready-to-disaster electrical infrastructure where the residents and industries of Plaridel, Bulacan will still have power and will not be affected by a heavy downpour.

On the other hand, this will primarily focus its setting on the most flood-prone areas within the vicinity of said municipality and its analysis will particularly be limited to flood-related outages and resiliency measures in order to maintain its alignment with the Energy Resiliency section of PEP 2023 - 2050. Moreover, historical flood data and outage reports would be the sole basis for this study. Furthermore, the financial aspect would only be analyzed in a limited one due to data availability.

Once this research proved to be successful, it will be beneficial to the local residents and government units (LGUs) in Plaridel, Bulacanas this will certainly improve public safety especially during the time of disasters whilst being able to maintain reduced economic losses and provide a reliable access to essential services. Moreover, the local electric utility such as Meralco will be able to gather necessary data that will allow them to provide a systematic blueprint that will serve as a guide for developing and/or installing upgraded distribution systems within the municipality that will further result in reduced operational costs of providing electricity in a state of calamities. Furthermore, this study can become a basis of the future researchers for their case studies especially in the aspect of energy resiliency for those located in flood-prone communities.

II. POWER RESILIENCE AND SYSTEMS RELIABILITY

Power Systems Reliability compromises the set principles and key metrics that serves as the basis for evaluation of operational performance as well as the continuity of the electrical services present all throughout the country. On the other hand, the Power Resilience or Energy Resilience basically describes the power system's ability to adapt and recover in a rapid manner from high impact events and/or disasters such as flooding [3]. In other words, power system resilience explains the ability of an electricity system to predict, withstand, absorb, adapt to, and quickly restore its operational capacity following disruptive events, e.g. typhoons, floods, earthquakes and long-term equipment failures, wherein the resilience that was mentioned focuses not on ability to survive shocks, but also the ability to serve vital loads (hospitals, water pumping, emergency facilities) and repair wider service as quickly as possible [4]. Recent literature redefines resilience as a planning and operational goal that compliments the traditional indices of reliability by focusing on high impact and low frequency events which are not well analyzed in the traditional indices [5].

Moreover, the concept of system reliability is fundamental in power systems planning and power systems operations especially because in a real-world application, system reliability is usually quantified by indices of outage duration, outage frequency, and outage customer impact such as SAIDI (System Average Interruption Duration Index), SAIFI (System Average Interruption Frequency Index), CAIDI, and MAIFI [6]. These indices are used by utilities to compare performance, focus on maintenance and report to regulators and customers on service quality, but planners and researchers warn that average reliability indicators do not necessarily represent the susceptibility to such events, hence resilience indicators and scenario analysis are becoming increasingly popular with SAIDI/SAIFI [7].

In other words, the enhancement of resilience and reliability is normally accomplished through a set of physical hardening, operational practices and investment in distributed and flexible resources. Such strategies and measures in an operational and organizational manner involve better prioritization of maintenance, pre-calamity (such as typhoons) isolation, and mutual assistance agreement [8]. Overall, the combination of engineering and operational measures lowers the risk of failure and decreases the time of recovery in case of failure.

III. DISASTER RISK REDUCTION AND MANAGEMENT (DRRM)

This system serves as the national guidelines for systematic approach in order to further identify, assess, and reduce the significant amount of risks both in human and non-human resources of the country during a disaster. With this, it basically tackles the prevention, mitigation, preparedness, response, and recovery phases during the said state of the country [9].

The very foundation of DRRM mainly includes the Republic Act No. 10121 (also known as the DRRM Act of 2010) which was made to establish the institutional frameworks and encouraged a multi-sectoral approach to all hazards which mandates national agencies, local government units and communities coordinate their efforts in hazard assessment, early warning, contingency planning and resilient infrastructure design [10]. Climatic and geological hazards, as well as preparedness and prevention, have been inducted in the abovementioned law to directly assist in hardening the energy sector against various hazards.

Moreover, the National Disaster Risk Reduction and Management Plan (NDRRMP) operationalizes RA 10121 by prioritizing the national priorities and directing programs on prevention/ mitigation, preparedness, response, and rehabilitation/ recovery. The new NDRRMP (2020-2030) and associated guidance literature actively promote hazard-informed land-use planning, build back better recovery principles, and mainstreaming of DRRM in the energy sector by making the energy sector conscious of DRRM requirements in terms of planning, siting, and operation of infrastructure to minimize exposure and vulnerability [11].

Overall, the energy sector needs effective DRRM that involves the coordination of the agencies (e.g., DOE, DILG, NDRRMC), local governments, utilities, and emergency services. The results of coordination are pre-disaster activities like shut-down of equipment, prestaged deployment of repair teams, prepositioning of mobile generation, and expedited permitting of temporary restoration. Adjunctive actions like disaster risk financing and insurance minimize the fiscal shock of significant outages and accelerates recovery by providing funds to carry out the repair of equipment and replacement in a shorter time.

IV. GEOGRAPHICAL INFORMATION SYSTEMS (GIS) MAPPING

Resilience planning cannot be done without the utilization of Geographical Information Systems (GIS) due to its capacity to combine spatial layers. In other words, this includes the application of 'spatial' data in order to properly analyze the geographic conditions of a specific area. This can be crucial especially in formulating certain plans in terms of the infrastructure projects that are expected to withstand disasters and such. With this, the exact location that must be the centralized concentration of the resiliency efforts (such as those that will be mentioned in the later part of this study) can be accurately determined [12].

Specifically, GIS aids the mapping of flood-inundation areas on distribution network layouts to calculate which lines and substations lie in areas prone to flood, or running scenario simulation (e.g., a 100-year flood) to estimate the area of outage and to rank investments. The evidence based decisions that are assisted by GIS results include elevation of equipment, routing of feeders, and location of new substations in low risk location. In the Philippine government setting, their spatial resource minimize uncertainty regarding the magnitude and scale of the hazards. With this, they are commonly utilized by the local government units (LGUs) and utilities in order to ensure the preparation of DRRM plans infrastructure location reports.

V. EXISTING STUDIES THAT FOCUSES ON RESILIENT ENERGY SYSTEMS

A number of Philippine-specific research and applied studies on resilient energy systems are continuously growing over the course of years. Such studies usually advise the use of hybridization, storage, and decentralization as resilience boosters and observe that the difficulties with it include component vulnerability to storms, maintenance capability in remote sites, and initial cost capital expenditure.

For instance, a study in 2023 mainly focused on the assessment of the design for a 'resilient' hybrid of PV-diesel/microgrid systems which acts as a response during disasters in the Philippine context. By the use of sensitivity analysis in the energy demand, it was able to determine the most optimal and resilient energy system for relief operations. As a result, the latter study proved to be beneficial for formulating resilience strategies at a community level [13].

Another study in 2022 addressed the existing problem of power supply restoration in the event of any power outages due to extreme weathers such as typhoons. According to it, network configurations act as the sole method of recovery during these times, which is unreliable and will only lead to a longer time of outage since it only relies on dispatching mobile power sources that are only limited in terms of its capacity. In order to overcome this, it proposed a type of co-optimization method whereas the distribution systems and the traffic network are directly coupled onto each other. In this way, the access points of mobile power sources are affected and shifted, which would certainly lead to a shortened amount of time during a power outage. Additionally, this method promotes a lesser routing and power generation costs of the above-mentioned components, as well as the amount of power losses compared to the traditional one that are widely used as of today. Hence, it was able to conclude that this algorithm is practical and feasible to be applied in a realistic setting [14].

Another example is the technoeconomic study of 634 off-grid islands that had examined hybrid PV-wind-battery-diesel microgrids and had given policy implications on government subsidies on the public to provide reliable and resilient electrification. Those research papers and data articles offer locationspecific and granular information that is of immense importance when making resilience investments in the electrification of islands and rural areas- and that they also show how GIS and spatial data feeds techno-economic models resilience planning [15].

With all of these, all of the abovementioned components, when assembled together (such as engineering hardening, DERs and microgrids, GIS-based prioritization, and DRRM institutional frameworks), lead to the creation of a multi-pronged approach balancing prevention, preparedness, physical actions, and prompt recovery.

VI. METHODOLOGY

This study employed the combination of descriptive and analytical approach whilst conforming with the engineering design in order to evaluate and propose a feasible plan and design that includes flood-resilient electric distribution systems that will be utilized by the above-mentioned municipality. In addition, the design process of this also conforms with the Philippine Energy Plan (PEP) 2023-2050 as the latter mainly emphasizes all the necessary inputs regarding resiliency of infrastructures and sustainability within the energy sector of the Philippines.

In specific, the descriptive-analytical approach are considered to be one of the most widely used approach and most appropriate one for studies that involves infrastructure resilience [16]. This is because the latter involves collecting all data relating to any outages due to flooding as well as asset-locations. In addition, this mainly utilizes the GIS for the sole purpose of mapping the data obtained. From the mapped data, there will be an opportunity to calculate all the vulnerabilities present, and once done, standard indicators such as fragility curves are utilized to quantify the resilience of the said system [17].

VII. STUDY AREA AND DATA COLLECTION

As noted in the introductory section of this paper, the municipality of Plaridel, Bulacan is cited as one of the places in the province that are very vulnerable to flooding especially those barangays and communities being situated alongside Angat River. The closeness of the river is also combined with the low topography of the area and exposure to rain and typhoon activities resulting in floods, which is a common occurrence and is a leading contributor to residential areas and other infrastructure. Particularly, this study covers a comprehensive collection and examination of extensive data to get an insight on the level of flood effects on the power distribution systems of the municipality. The main source of the determination of flood prone areas and frequency of flood occurrences in the study area was based on the past flood maps, as provided by the respective agencies: Department of Science and Technology (DOST),
Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA), and the Municipal Disaster Risk Reduction and Management Office
(MDRRMO). Additional information, such as the power outage logs and restoration schedules were also obtained on the local energy company to match the floods with power cuts and infrastructure damage.

Also, this study was carried out using sophisticated spatial analysis procedures using Geographical Information Systems (GIS) mapping to combine and analyze the acquired information. The GIS application allowed drawing the most important data regarding the geographic location of transformers, substations, power lines, and other key elements of the electrical network in connection with previously identified areas of flood risks. This spatial relationship was useful in getting clues on the components of the distribution system that were most susceptible to inundation. The geographic coordinates of the electrical assets was then used to create layered maps which depicts the spatial overlap as well as the extent of exposure of the power infrastructure to flooding. The process was not only beneficial in increasing the knowledge on the vulnerability of floods, but also assisted in determining the areas of safety and where to relocate or elevate important equipment. This combination of past flood records and GIS-based mapping enabled the study to provide a more detailed and evidencebased basis on how to recommend floodresilient approaches to designing the power distribution network in Plaridel.

VIII. IDENTIFICATION OF RISKS AND VULNERABILITIES

All flood-prone distribution components were categorized based on each component’s exposure to flood during typhoons. The exposure level was determined by the proximity to flood-prone zones as recorded by the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) and the local MDDRMO. In specific, each asset were categorized into specific classes, namely: low, moderate, or high risk according to their respective elevation and physical sensitivity to any damage due to exposure on floods.

On the other hand, the vulnerability assessment was guided by the parameters of the Disaster Risk Reduction and Management (DRRM) framework as the latter was mainly focused on emphasizing the identification of any risks, mitigation, and the preparedness during the time of calamities, even on the local assets of a given municipality [18]. In specific, the evaluation considered the following factors:

a) Elevation of the assets, which includes the vertical clearance between the base of any said equipment and the maximum recorded flood
level;

b) Capability to waterproofing, to which it includes the assessment of the environmental sealing and ingress protection of the enclosures, particularly in switch gears and control panel; and

c) Accessibility during the flooding events, that refers to the ability of all maintenance personnel to reach all the electric distribution systems on times of calamity and restore the latter
regardless of the current situation

Once all these were done, there was an indicator that corresponds to a descriptive score based on the field survey data and technical specifications. When the scoring was done, it was then transmutted into a vulnerability index, which refers to a composite measure of a country or area's exposure and adaptability to the impact of a certain change in the existing condition of the said area [19].

The results of the latter part served as the analytical foundation on determining the distribution assets that must be prioritized on being structurally elevated and/or waterproofed. In addition, the utilization of the descriptiveanalytical approach allowed this study to be able to evaluate the systems' weaknesses in an objective manner whilst maintaining true to its goal to formulate flood-resilient distribution strategies that aligns with the PEP 2023-2050.

IX. DESIGN OF FLOOD-RESILIENT ALTERNATIVES

In relation to the existing problem that was presented on the earlier parts of this paper, two main engineering solutions were proposed and analyze, namely:

a) Waterproof switch gears, which refers to the electrical enclosures that are designed with a built-in watertight seals and corrosion-resistant materials that are capable to withstand any conditions once submerged to flood; and

b) Elevated transformers, whereas it refers to the distribution transformers that are to be installed in a reinforced steel and/or concrete platforms that are beyond that of the maximum recorded flood levels on each respective area.

In addition, these design proposals were evaluated in terms of its feasibility, efficiency, compliance with the national standards, and its operational costs to ensure the maximum resilience target was attained.

X. VALIDATION, COST ANALYSIS, AND ALIGNMENT WITH PEP 2023-2050

All proposed configurations were reviewed by the experts in the field of study to ensure its compliance with the Philippine Electrical Code (PEC) standards [20]. In addition, a cost-benefit analysis was conducted in order to compare the requirements for investing in the proposed alternatives to the existing costs of installing the regular ones that exists today. Also, an estimation regarding the reduction in outage-related economic losses was further performed and presented on the later part of this study in order to allow an easier comparison of the benefits of the proposed alternatives once it was installed.

Furthermore, the final step involved the formulation of flood-resilient distribution system plan for the said municipality that integrates all the designs that were evaluated on this study. The said plan was also mapped in consideration of the existing strategic objectives as stated on the PEP 2023-2050. In specific, the Energy Resiliency Policy Framework section of the said plan was integrated and adapted in order to ensure that all the recommendations to be indicated on this study will contribute to a long-term energy reliability, preparedness, and safety of the given municipality.

XI. RESULTS AND FINDINGS OF THE STUDY

This section mainly includes the outcome of the evaluation performed for the municipality of Plaridel, Bulacan based on the combination of descriptive and analytical approach that was utilized for this study. In specific, this section includes the: summary of the flood exposure and vulnerability mapping of the existing power distribution network of the said municipality, estimation of the probabilities of component failure [of the latter distribution networks], and the amount of performance gain of the given distribution lines through the integration of flood-resilient designs. Furthermore, the analysis of this study integrated all the municipal records of outage incidents and the outputs from the resilience modeling tools that also aligns with the PEP 2023-2050.

Also, the Bulacan provincial monitoring dashboard and the MDRRMO records and postings established the alert levels for local gauges of water rise. These were utilized in order to anchor the severity of flood scenarios and events in the simulations. Moreover, the recent regional incidents corroborate with the data that were mentioned above.

The results of the simulation show that flooding is a significant threat to the current distribution infrastructure in Plaridel, especially to those that are often subjected to floods in flood-prone barangays along rivers and lowlands. The state of infrastructure as it is currently found before mitigation, which is labeled as the baseline scenario, had high levels of component failure when the depth of the floods were above 1.0 to 1.5 meters, a range that is usually experienced during the monsoon seasons and extreme rainfall in the municipality. Additionally, switch gears and distribution transformers were especially vulnerable because they were installed relatively low and had a low resistance to extended exposure to water. In comparison, the suggested mitigation scenarios, which included raising transformers to a height of at least 2.0 meters and putting waterproof switch gears, led to significant lowering of the number of failures, customer outages, and system interruption indices including SAIDI (System Average Interruption Duration Index) and MTTR (Mean Time to Repair). With this available results, the importance of physical hardening measures were underscored in order to enhance the resiliency of the distribution systems.

Moreover, the findings of this study was congruent with the PEP 2023-2050, wherein the climate-resilient energy infrastructures was emphasized as a priority to ensure that a reliable electric supply was maintained amid the hazards due to climate change.

XII. EXPOSURE TO FLOODS AND VULNERABILITY MAPPING

The latest available version of flood records in the municipality of Plaridel, Bulacan was found from the DOST-PAGASA's monitoring data on 2024. According to the given data, Banga 1st and Parulan, both barangays that were situated along Angat river, frequently reaches 2.5m (alarm level) of water and occasionally exceeds 3.5m (critical level) [21], [22]. As a result, these events creates a direct impact on the local electrical distribution system, such as the pole-mounted transformers and outdoor switch gears, especially on the ones that are situated in particularly low portions of the above-mentioned areas.

With the use of GIS overlay analysis (available in the municipality of Plaridel), a total of 128 power distribution assets were mapped across the given municipality. In addition, each asset was overlaid on the floodplain map of the given municipality and designated a scoring system for the amount of exposure they experiences. In specific, this scoring method included the assessment for the exposure to flood-induced damages and were classified as follows: high-risk, moderate-risk, and low-risk. This classifications were also tabulated in order to give the criteria on when to consider an asset as low-risk, moderate-risk, and a high-risk one.

Classification	Criteria
High-Risk Assets	Greatly exposed to floodinduced water levels as it is situated on a low elevation area without any waterproof enclosure
Moderate-Risk Assets	This includes the assets that has a partial protection from flood (e.g., elevated location but without a properly sealed switch gear)
Low-Risk Assets	Installed in an elevated area and/or in locations outside the mapped flood extents.

Table 1. Classification of the power distribution assets based on their relative location and enclosures.

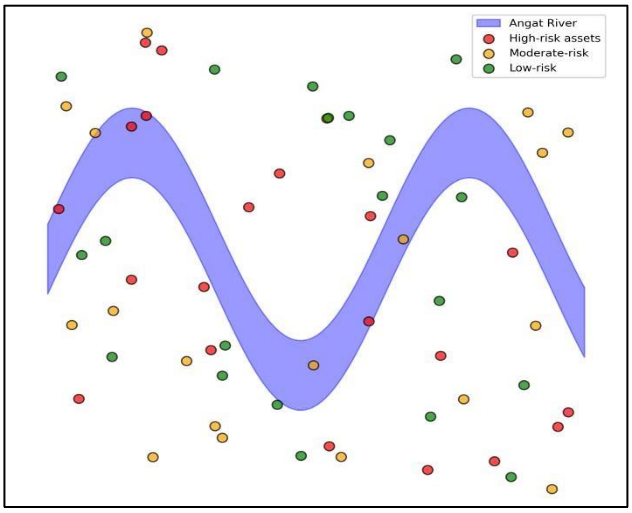

Figure 1. Flood hazard overlay map of the municipality of Plaridel that shows the locations of distribution assets such as transformers and switch gears and their respective classifications within 100-year floodplain zones.

As illustrated on Figure 1, the spatial risk analysis of electrical distribution systems in Plaridel, Bulacan demonstrates a high level of concentration of the infrastructure at risk due to floods. The high-risk assets were considered to be 54 units, which make up around 42 percent of the total assets under consideration. These properties are concentrated on the barangays close to the Angat River, especially Parulan, Banga 1st and the low-lying parts of Poblacion. The fact that these regions are close to the large waterways, and are characterized by relatively low levels, makes them highly vulnerable to flooding during construction of heavy precipitation and river water overflow.

On the other hand, 38 assets (estimating 30 percent of the total) were found to be moderate-risk. This majorly includes the assets that are usually found in the transitional areas, which undergo occasional flooding especially during moderate-intensive and severe weather conditions. Though these places might not be flooded when a minor flooding occurs, frequent exposure of floodwater to the electrical equipment during extreme situations remains a significant danger to the stability and usefulness of electric equipment. Such exposure may over time lead to faster component degradation, higher frequencies of failure and it may take longer time to restore the whole component after a flood occurrence.

Lastly, the remaining 36 assets (about 28%) were considered to be low-risk. Such assets are located mostly in places that are of high elevation or within the areas with better drainage infrastructure where the frequency of floods is minimal or short lived. Although the threat to these assets were relative to short term, their classification does not necessarily nullify the risk in the scenario of climate change and its unpredictable flooding patterns (which increasingly increases over time). The spatial distribution of the types of risk observed confirm the first hypothesis of this study that a large percentage of distribution transformers and pole-mounted switch gears in Plaridel have been subjected to flood conditions many times during moderate to severe floods. The concentration of high- and moderate-risk assets around the riverbanks and flood-prone areas is an indicator of systemic weaknesses in the current distribution network. Besides, the results align with the long-term flood observation and damage records reported on the provincial level, which substantiates the integrity of the risk assessment and highlights the urgency of the specific flood-resistant mitigation measures in the most at-risk zones.

XIII. FAILURE PROBABILITY OF POLEMOUNTED TRANSFORMERS AND OUTDOOR SWITCHGEARS

In order to determine the failure probability that was highlighted in this section, the specifics from the figure 1 was utilized. This was also done due to the limitations on the availability of a GIS software that can be used for this particular research. Adapted from the research of Leandro et. al., a fragility curve was developed from the available local outage data and the damage functions in relation to the depth of the flood.

Flood Scenario	Ave. depth (m)	Switch gear Prob. Failure	Transformer Failure Probability
Alert Level	1	0.35	0.28
Alarm Level	2.5	0.78	0.62
Critical Level	3.5	0.93	0.87

Table 2. Summary of the failure probability of switch gears and transformers depending on the depth of the flood.

In order to arrive on this data, the following formulas were used:

For the switch gears:

$$(h) = \frac{1}{1 + e^{-(-a+bh)}}$$

For the transformers:

$$(h) = \frac{1}{1 + e^{-(-a+bh)}}$$

Where:

- (h) = failure probability at certain flood depth level (in meters)
- a = component sensitivity parameter (a=3 for switch gear; a=3.5 for transformer)
- b = refers to the slope/rate at which the probability is directly proportional with depth (b=1.4 for switch gear; b=1.3 for transformer)
- h = depth of the flood water relative to the elevation of the components

In specific, this section was done by integrating the water depth or the exposure of the two asset classes that were previously defined with the empirical failure observations from the outage logs and literature fragility curved that were scaled to the local equipment types.

Based on the given table of values, on the event of a moderate flood scenario (categorized as “Alarm Level” with an average water depth of 2.5m), the failure probabilities for a pole-mounted distribution transformer is equal to 62%, while obtaining a 78% for outdoor non-waterproofed switch gear. However, when the flood scenario rose to the Critical Level, the failure probabilities rose as well at above 90% for the switch gear and above 85% for the transformer of the same mounting. Additionally, historical reports available from the DSWD and MDRRMO bulletins support the occurrence of the localized outages during such events, which were also utilized in order to calibrate the findings of the said model.

Overall, it can be seen on the table itself that the depth of the flood’s water level is increasingly proportional with that of the failure probability of the switch gears and transformers that were mounted without any waterproofing. Also, this further signifies that rapid degradation can be seen on the components when exposed to critical thresholds of water. When repeatedly exposed, insulation breakdown, corrosion, and mechanical damage often results to permanent failure rather than a temporary outage. With this, the urgency to mitigate any exposure to flood can be highlighted rather than solely relying with postrepairs.

XIV. EFFECTIVENESS OF PROPOSED DESIGNS

Compiling all the available resources and running a prepared code in a cloud-based platform for executing codes such as Python, the following data were obtained:

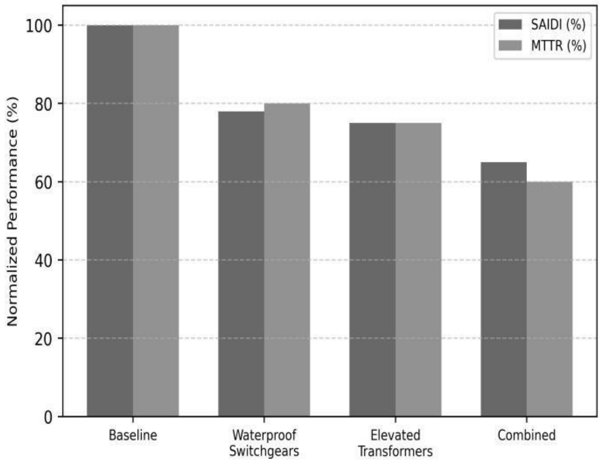

Figure 2. Comparison of the failure probabilities after improvements in percentage.

This data were made in order to evaluate the expected performance improvements to the existing distribution networks once executed.

From the table, the categories were classified into four (4):

a) Baseline - refers to the existing mounting positions of the components (exposed to flood; not waterproofed)
b) Waterproof switch gears
c) Elevated transformers
d) Combination of waterproof switch gears and elevated transformers

Based on the findings presented on the table, from being totally (hundred percent) vulnerable due to flood, waterproofing the switch gears can reduce its failure rates by up to 65%, translating to a SAIDI improvement of up to 22%. On the other hand, when the existing transformers were elevated than the usual, their exposure were minimized to up to 80% (which translated to an improved SAIDI of up to 27%). Lastly, when those two were combined, it will yield to the highest improvement percentage (up to 35% SAIDI reduction and up to 40% MTTR percentage decrease). This data only further shows the feasibility of incorporating the abovementioned improvements in a simultaneous manner. Additionally, the performance trends on this table can be further justified with the previous resilience modelling studies for various distribution systems subjected to hydrological hazards.

XV. ECONOMIC ANALYSIS

The primary goal of presenting an economic analysis section in this paper is to evaluate on whether the implementation of flood-resilient mitigation strategies in electrical distribution systems in the given municipality is financially feasible (with long-term benefits) or not. In line with the PEP 2023-2050, this economic analysis allows for a more comprehensive evaluation to justify the proactive infrastructure modifications as suggested by this research.

	Elevated Transformers	**Waterproof Switch gears**	**Combined Mitigation**
Initial CAPEX per unit	at least PHP 150k	at least PHP 40k	at least PHP 190k
Replacement Risk	Reduced	Moderately reduced	Minimal
Payback Period	4-6 years	4-5 years	3-5 years

Table 3. Comparative economic performance of flood-resilient mitigations.

For the primary capital costs (CAPEX) of elevating transformers, the construction, relocation, modification of connections, and compliance with safety hazards were considered. Based on the prevailing estimates in the industry and recent utility projects, the cost of doing the latter ranges from PHP 120 000 to PHP 180 000, depending on the conditions of the site and the capacity of the transformer to be mounted. For the sole purpose of this analysis, the average cost amounting to PHP 150 000 per unit was assumed. Similarly, an average cost of PHP 40 000 per single unit of waterproof switch gear was estimated. This was due to various considerations (which are not limited to) retrofitting, installation costs, and testing. For the combined mitigation, the sum of the abovementioned two was presented as the minimum costs as no available data was gathered for the specific costing of the latter.

Additionally, the replacement risk was evaluated based on the effectiveness of the mitigation presented. This was due to the fact that the proposed components were likely to be rarely exposed to floods since elevation and waterproofing was already made.

For the payback period, conservative assumptions were made limited to 3 to 5 years. This was because a shorter payback period makes the investment economically attractive, especially when the frequency of flood events due to the climate change was considered.

XVI. IMPLICATIONS FOR ENERGY RESILIENCY AND POLICY ALIGNMENT

This particular study has direct implications with the existing energy resiliency planning in both municipal and national level. According to the PEP 2023-2050, the necessity to have climate-resistant infrastructures that will guarantee the adequate supply of electricity in the event of rising climate risks continue to surge over time. In relation to this, the suggested mitigation measures were drafted to align with this policy framework since they provide a practical solution to the problem that are engineering-based and can be implemented incrementally.

In addition, this study provides an evidence-based support for prioritizing investments such as mentioned above by quantifying the benefits of the flood-resilient designs (payback period). Moreover, this research also establishes the practicality of performing complex resilience investigations by utilizing free, open-source tools and data, and other strategies that are accessible to the local government units, utilities, and academic programs with low resources.

XVII. SUPPLEMENTARY MITIGATION STRATEGIES FOR FLOOD-INDUCED POWER OUTAGES

While the elevation of distribution transformers and the installation of waterproof switch gears significantly enhance flood resilience, additional mitigation strategies may further reduce the frequency, extent, and duration of power outages in Plaridel, Bulacan. These supplementary measures address structural, operational, and system-level vulnerabilities identified through the spatial and reliability analyses conducted in this study.

One effective supplementary strategy is the deployment of automated sectionalizing and recloser switches within flood-prone feeders. By enabling rapid isolation of faulted or inundated segments, sectionalizing limits outage propagation and allows unaffected areas to remain energized. This is particularly beneficial in Plaridel, where flooding is spatially concentrated near the Angat River and does not uniformly affect all barangays. Automated switching can therefore significantly reduce system-wide outage duration during localized flood events.

Another complementary approach is distribution network reconfiguration, including the adoption of looped or ring-type feeder arrangements in critical areas. Unlike conventional radial systems, looped configurations provide alternative power paths, allowing supply restoration from adjacent feeders when one section is compromised by flooding. This enhances system redundancy and improves overall reliability during extreme weather conditions.

The integration of distributed energy resources (DERs) also presents a viable supplementary mitigation option. Communityscale solar photovoltaic systems with battery energy storage, when strategically installed at elevated locations such as schools, evacuation centers, and municipal facilities, can provide backup power during prolonged outages. These systems support critical services and reduce dependence on the central grid during flood events.

In addition, flood-aware protection and monitoring systems can further strengthen resilience. The use of water-level sensors integrated with protective relays or supervisory control and data acquisition (SCADA) systems enables early detection of rising floodwaters and allows for preemptive isolation of vulnerable equipment. Such measures reduce the likelihood of catastrophic equipment damage and improve post-flood restoration efficiency while enhancing personnel safety.

Collectively, these supplementary mitigation strategies reinforce the primary flood-resilient interventions proposed in this study and provide a holistic framework for strengthening energy resiliency in Plaridel, Bulacan in accordance with the Philippine Energy Plan 2023–2050.

XVIII. COMPARISON OF FAILURE PROBABILITIES UNDER SUPPLEMENTARY MITIGATION STRATEGIES

This section presents a comparative assessment of the effective failure probabilities of distribution transformers and switchgears under flood conditions when supplementary mitigation strategies are implemented, relative to the baseline condition where assets are left unprotected. The values represent relative reductions derived from reliability engineering principles and outage propagation behavior, rather than direct waterproofing effects.

Mitigation	**Transformer Failure Prob.**	**Switchgear Failure Prob.**	**Effect on System**
Baseline	High (0.60-0.75)	High (0.65-0.80)	Direct Exposure
Automated Section. & Reclosers	Moderate (0.45-0.55)	Mod.-High (0.55-0.65)	Limits outage propagation
Looped Feeders	Moderate (0.40-0.50)	Mod. (0.45-0.55)	Provides alternate supply paths
Distributed Energy Resources	Reduced (0.30-0.40)	0.35-0.45	Maintains local supply
Flood-Aware Protection & Monitoring	Moderate-Low (0.35-0.45)	Mod.-Low (0.40-0.50)	Prevents catastrophic damage
Elevated Transformers & Waterproof Switch gears	Low (0.10-0.20)	Low (0.10-0.20)	Direct asset protection
Combined Primary and Supplement Measures	Very Low (0.05-0.10)	Very Low (0.05-0.10)	Maximum system resilience

Table 4. Comparison of effective failure probabilities under flood conditions.

Based on the table above, in baseline conditions where transformers and switchgears are left unprotected, failure probability increases sharply once flood depth exceeds 1.5– 2.0 m. Equipment exposure results in direct failures and cascading outages, particularly in radial feeder configurations common in Plaridel. On the other hand, the automated sectionalizing and recloser switches do not prevent equipment failure, but they significantly reduce the effective system failure probability by isolating flooded segments. Transformers downstream of isolated sections remain energized, reducing the number of affected customers and limiting outage spread. For the distribution network reconfigurations, looped or ring-type feeders further reduce effective failure probability by allowing alternative power paths. Even when transformers or switch gears fail locally, supply can be restored from adjacent feeders, lowering the functional impact of failures.

Additionally, the distributed energy resources reduce functional outage probability rather than physical failure probability. While grid components may still fail, critical loads remain powered, resulting in a significantly lower effective failure rate from the customer perspective. On the other hand, during floodtriggered isolation, it prevents prolonged submersion and secondary damage. Although equipment may still be temporarily disconnected, the likelihood of permanent failure is reduced, leading to lower effective failure probabilities and faster restoration.

When all of these were compared with the direct asset hardening, the latter provides the largest reduction in physical failure probability, outperforming all supplementary strategies when applied alone. However, when combined with supplementary measures, the system achieves the lowest overall failure probability, supporting a layered resilience approach.

XIX. LIMITATIONS AND AREAS FOR FURTHER RESEARCH

While the results of this research are highly informative, various limitations were also acknowledged. For instance, the depth of the flood that was utilized were only based on the existing available records and representative distributions, rather than relying on the highresolution and site-specific models. Hence, detailed flood modeling could be further done in order to refine the accuracy of the estimates on the exposure of each component.

Moreover, the fragility curves were only calibrated using limited data points and assumptions regarding the failure probabilities of the components. Although the methods of this research (logistic model) was aligned with the widely accepted model, further researches could incorporate empirical failure data from the utilities in order to ensure that the calibration was accurate that will yield to a more valid results.

Lastly, the study mainly focused with the physical hardening interventions and only specified model operational strategies such as network reconfigurations and distributed generation or microgrids in a limited manner. Further in-depth incorporation of these strategies in future analysis would significantly offer a more in-depth evaluation of the resilience choices.

XX. CONCLUSION

This study established that the effects of floods in Plaridel, Bulacan causing power cuts can be greatly reduced by using flood resilient design of the distribution system, which are presented in this paper as elevated transformer and waterproof switch gears. The study modeled the quantification of the vulnerability of a current infrastructure and the effectiveness of mitigation measures proposed through a descriptive-analytical approach supported by the use of probability-based fragility modeling and Monte Carlo simulation. The results strongly suggest that the existing distribution system is very susceptible to flooding and the probability of failure rises to sharp levels as the depth of the floods rises. Without mitigation, the chances of moderate to serious floods causing widespread component failures, extended interruptions, and severe disruptions to necessary services were significantly high. In comparison, the suggested mitigation measures significantly decrease the likelihood of failure, downtime and system outage indexes.

Grounding up transformers and waterproofing switch gears are a good approach to decoupling vital electrical equipment from flood exposure, as well as increasing resistance to water entry. These measures, when combined, can offer a highly resilient and low-cost method of enhancing energy resiliency.

The findings of the study conform to the aims of the Philippine Energy Plan 2023-2050 and facilitate the consideration of the issues of climate resilience in the planning of the distribution system and investment decisions. Also, the fact that the tools that were used are free and based on the browser shows that high resilience analysis can still be conducted with minimal resources. Finally, the study can be added to the existing literature on infrastructure resilience and available as a practical framework to help municipalities and utilities reduce the effect of power outages caused by floods. With this, the municipality of Plaridel (and other ones that are within the flood-prone areas) can become better prepared by adopting flood-resistant designs of their distribution systems and strengthening future energy security, which safeguards the interests of people and secures a more resilient future whilst promoting a sustainable development.

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