University of Rwanda

College of Economics and Business

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IMPACTS OF POWER DISTRIBUTION FEEDERS UPGRADING POLICY ON THE RELIABILITY OF ELECTRICITY SUPPLY

EVIDENCE FROM RWANDA

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DECLARATION

I, **Jimmy Christian MUNYEMANZI**, hereby declare that the work presented in this Master's Dissertation is my original work, and has not been presented for a degree at the University of Rwanda or any other university. All sources of materials that will be used for this Dissertation work will have been fully acknowledged.

Signature: Date: **July 1st, 2021**

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Date: **July 1st, 2021**

DEDICATION

I dedicate this Master dissertation to God all mighty, my creator and protector. The only reason I made it this far.

I also dedicate this work to my late Mother MUKABEZA Phoebe, for her love and all her sacrifices to get me this far.

I dedicate this work to my brother, my sister, my fiancé, my workmates and all my friends for their unconditional support during this academic journey.

Special thanks go to Rwanda Utilities Regulatory Authority management, for providing all I needed to study this Master's program.

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ABSTRACT

The national Energy Sector Strategic Plan 2018/19-2023/24 has set a priority to improve industrial competitiveness, through increased reliability of electricity supply. For this to be achieved, the Rwandan government has preserved a huge amount of money to construct new power infrastructures and to upgrade and rehabilitate the existing systems. In this regard, during the past three years, a number of projects targeting to increase the reliability of electricity supply were commissioned, corresponding to huge investments. In this study, we analyse the impacts of these investments on the improvement of electricity supply reliability, by using administrative power outages across various distribution feeders in Rwanda, gathered from the national electric utility. The electricity supply reliability is expressed in terms of the frequency and duration of power outages at different distribution feeder lines. This study exploits the plausibly exogenous variation in the implementation of the policy, to measure if there have been changes in power outages duration and frequency. The results show, the upgrading and rehabilitation of main power distribution feeders across the country have reduced the duration and frequency of power outages. In addition, the impact becomes more significant if we omit the effects of other unobserved variables. The study also investigated the impact of Covid-19 on the reliability of the electricity supply. It was found that the pandemic increased the duration and reduced the frequency of power outages.

Key words: electrical power systems, power distribution feeders, power system reliability, power outages.

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ABBREVIATIONS AND ACRONYMS

ASAI:	Average Service Availability Index
AUFLS:	Automatic Under Frequency Load Shedding
CAIDI:	Customer Average Interruption Duration Index
CAIFI:	Customer Average Interruption Frequency Index
CIII:	Customer Interrupted per Interruption Index
DiD:	Difference in Differences
ESSP:	Energy Sector Strategic Plan
EUCL:	Energy Utility Corporation Limited
FE:	Fixed Effects
FUP:	Feeder lines Upgrading Policy
GDP:	Gross Domestic Product
GLM:	Generalized Linear Model
HV:	High Voltage
IEEE:	Institute of Electrical and Electronics Engineers
LV:	Low Voltage
MAIFI:	Momentary Average Interruption Frequency Index
MV:	Medium Voltage
RURA:	Rwanda Utilities Regulatory Authority
SAIDI:	System Average Interruption Duration Index
SAIFI:	System Average Interruption Frequency Index
SMEs:	Small and Medium-size Enterprises
UFLS:	Under Frequency Load Shedding

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CHAPTER ONE: INTRODUCTION

1.1. Background

An unreliable electricity supply system constitutes one of the barriers to economic growth in many developing countries. An electric power system is a network that consists of three main parts namely generation, transmission and distribution systems. In a power system, different sources of energy like; hydro, solar, coal, tidal, nuclear, methane, peat, diesel, etc., are converted into electrical energy. The generated power is transferred to various substations through high voltage power lines. From the substation, medium voltage power lines distribute the power to different distribution transformers, where it is stepped down to appropriate levels of voltages as required by various customers (Mehta, 2006). The level of voltage at which electricity is transmitted and distributed varies from country to country. In Rwanda, electrical power is transmitted at 110 and 220 kilovolts and it is distributed at 30 and 15 kilovolts for big consumers in rural and urban areas respectively, 0.4 kilovolts for medium consumers and 220V for small consumers. Figure 1 shows the different parts of a power system.

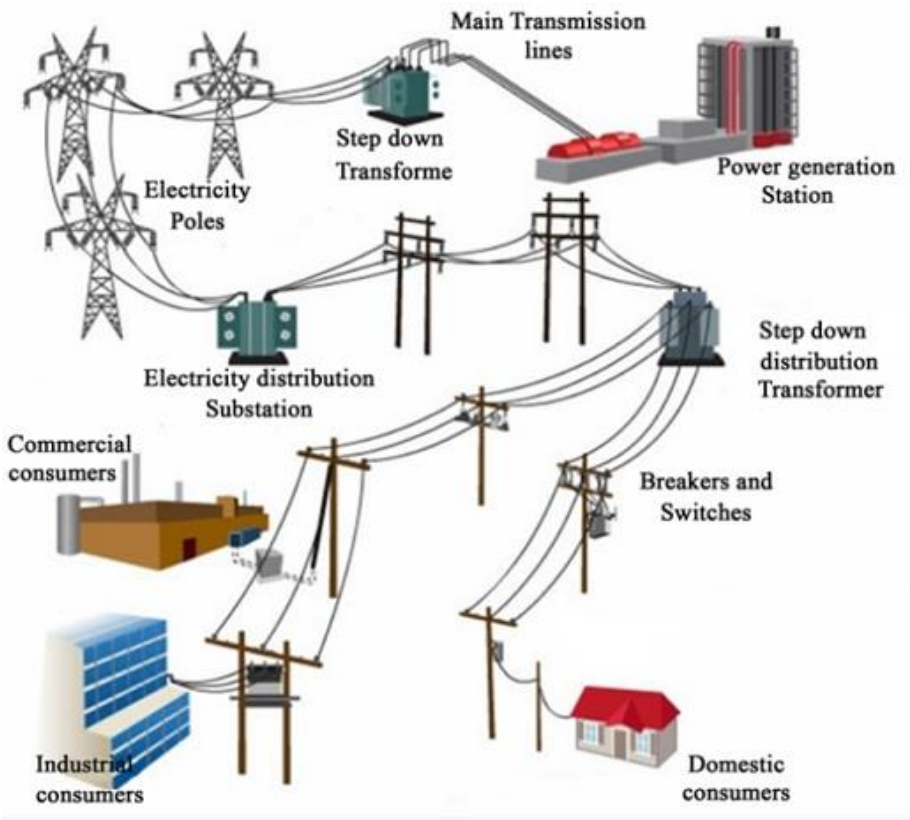

Figure 1: Electric power system

Source: http://elecengworld1.blogspot.com

The continuous operation of power systems, also known as the reliability of power systems, is often disrupted by power outages and failures resulting from various causes. The fact that power systems are spread over large geographic areas also increases the probability of facing different faults and failures (Hassan & Takawira, 2019). (Hachimenum, 2015), defines a power outage as a short or long-term absence of electricity in a given area or section of a power system. Power outages can be planned or unplanned, and they may raise from different causes. (Sinan , 2015), classifies power outages into three main categories namely momentary, sporadic and chronic outages. Momentary outages last for a very short time. Sporadic outages arise from severe weather conditions such as storms, floods, or thunderstorms and they may cause long-lasting systems blackouts. On the other side, chronic outages are mostly triggered by poor system planning and operation, generation deficit, systems internal faults, systems overloading, infrastructure aging, lack of maintenance, etc. According to (Lassana & Abdoulaye, 2013), power outages do not only affect people's routine living styles but also their business. Power outages may result in huge monetary loss for individuals, enterprises and countries in general. This justifies the reason why, countries around the world, especially developing countries, have been implementing different policy measures to minimize and if possible eradicate power system outages.

The Rwandan grid has experienced notable power outages over the past five years, although recently the trend has been downward. Ninety-three main power distribution feeders, all around the country, have recorded significant numbers and durations of power outages. Among the reported causes, unplanned power outages had the biggest share (99%), and were mainly caused by; blackouts, earth faults, emergency works, load shedding, loss of supply, major interruptions, overloads, overcurrent, overvoltage, under-voltage, under-frequency, switching operations and other unidentified works (EUCL, 2016; 2017; 2018; 2019; 2020). Figure 2 shows the shares of the different causes of power outages in Rwanda, from January 2016 to October 2020.

Blackouts are defined as a total cut of an electrical network, and may arise from different causes such; imbalance between the generation and demand, human error and other faults such as over-voltage, under-voltage, over-frequency, under-frequency and earth faults.

Overcurrent faults mainly arise from the system overloading, earth faults and short-circuit. Short-circuit faults are caused by the insulation failure between phase conductors or between earth and phase conductors or both.

Over-voltage and under-voltage faults are reported when the voltage of electrical power system rises or falls above or below the normal system voltage, respectively. Like the majority of other faults in the electrical power system; over-voltage faults can be caused by internal and external causes. The internal causes include system equipment failure and sudden load switching, while external faults are mainly related to lightning strikes.

Over-frequency and under-frequency faults are reported when the frequency of electrical power system rises or falls above or below the normal system frequency, respectively. The normal system frequency varies from country to country, where it is 50 hertz for some countries and 60 hertz for others. For Rwanda the allowed power system frequency is 50 hertz. Over and under frequency faults are mostly caused by imbalance between the generation and demand, and they can also arise from causes related to poor electrical system design. An earth fault is defined as an unintentional fault between the live conductor and the earth. When there is an earth fault, the path of electric current through the system is shorted to the ground. This results in increased current flow through the system, which damages the system equipment. Under-frequency fault can also be reported as a result of Automatic Under Frequency Load Shedding (AUFLS), which is a new strategy, applied by power systems operators, to prevent electric power system from incurring widespread blackouts due to imbalance between generation and demand. In the case where AUFLS is applied, some feeders are set to be more sensitive to decreases in the frequency, and to get disconnected as quickly as possible when the frequency decreases to a pre-set value.

From January, 2016 to October, 2020; among the reported power outages, over-current, earth faults and under-frequency related power outages had the biggest shares as compared to other types of power outages that were hindering the continuous operation of the Rwandan power system. The figure below shows the cumulative shares of various causes of power outages, on the Rwandan power system from January, 2016 to October, 2020.

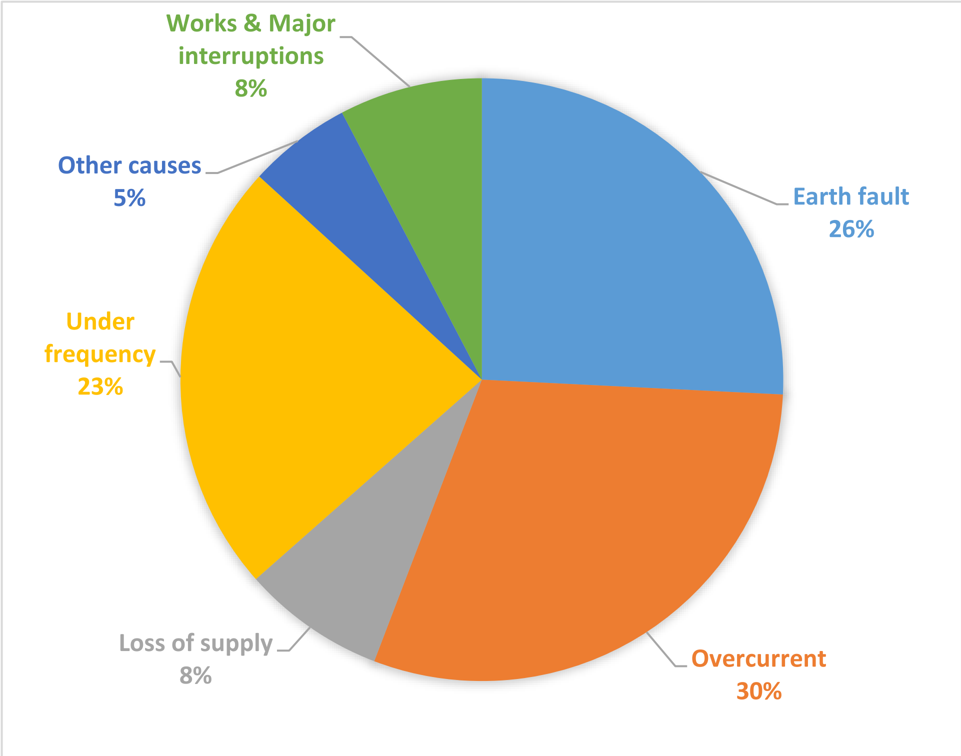

Figure 2: Shares of different causes of power outages, January 2016 to October 2020

Source: EUCL

International and national reports confirm that Rwanda has made notable progress in reducing power system outages during the same period. From January 2017 to July 2018, the frequency of outages in power distribution systems reduced from 400 to 150 outages per week (World Bank, 2018). The same report also confirms that the number of systems blackouts recognized a downward trend. (RURA, 2019) admits that the total number of outages reduced from 7471 to 2687 from July 2018 to June 2019, and their duration reduced from 2372.5 to 1632.1 hours in the same period. The journey to a more secure and reliable power system continues. The country has an ambitious target to reach universal access and to reduce the average number and average duration of power outages form 229.3 and 36 hours per year in 2018 to 91.7 and 14.2 hours per year by 2024 respectively. To achieve this, increased investments had to be directed in the sector to construct new power infrastructures, and rehabilitate or upgrade the existing ones. The rehabilitation and upgrade of LV and MV networks, including the development of the Kigali ring network, the construction of new HV line and upgrade from radial to robust ring network, and the upgrade of main distribution feeders and various substations linking the transmission and distribution networks were among the key policy interventions (Mininfra, 2018). Annex 1 shows the list of projects that were commissioned during the study period and the corresponding beneficiary feeders.

In this research, we evaluate he causal impact the power distribution feeders upgrading policy (FUP) on the reliability of electricity supply. The FUP represents the various investments made by the Rwandan government, to address the reliability issues of the national power systems. It covers all the investments made in the power system sector including; the upgrade of existing power infrastructures and the construction of new power infrastructures as shown in annex 1..

1.2. Problem statement

Over the last years, GoR has invested huge amounts of money in the energy sector to ensure a more reliable and stable power system. These amounts of money were either from different donors or collected from taxpayers, and could have been used for other sorts of country's development purposes. GoR believed that more investments in the strengthening of power infrastructures would contribute to the improvement of the national power system reliability, and therefore promote industrial competitiveness. A budget of $240million was estimated for the national grid reliability improvement purposes (Mininfra, 2018) . The country has now started the third year of the 2018 to 2024 Energy Sector Strategic Plan. A number of projects including new substations, power transmission and distribution lines were constructed, others got rehabilitate and upgraded. Scrutinized impacts assessments are needed to evaluate the contribution of these projects and the corresponding investment amounts on the power system reliability.

1.3. Objectives of the research

1.3.1. Main objective

The main objective of this research is to analyse the impacts of power distribution feeders upgrading policy on the reliability of electricity supply.

1.3.2. Specific objectives

- To evaluate the impacts of these investments on the reduction of power outages in terms occurring frequency and duration.
- To investigate others factors that may be affecting the national power system reliability;

- To investigated the impact of covid-19 pandemic on the reliability of Rwandan power system.

1.4. Scope of the research

According to (Rabah, Hassiba , & Djamil , 2017) as 90% of power systems failures occur in the distribution part where various consumers are connected, it is mostly recommended to analyse the reliability of a power system using indices that are directly related to the customer. The IEEE standard number P1366, "Guide for Electric Distribution Reliability Indices" has defined generally accepted reliability indices for power distribution systems, namely; SAIDI, CAIDI, SAIFI, MAIFI, CAIFI, CIII and ASAI. However, these indices are not considered in this research because, there was no sufficient information on them during the research period. Classical methods for power system reliability evaluation such as outage occurrence frequency and duration were used in this research. According to (Hassan & Takawira, 2019) power systems outages, occurrence frequency and duration are among the key system reliability indicators. The lesser the frequency of power outages and the smaller their duration, the more reliable and stable a power system is. The research was conducted from January 2016 to October 2020 and covers the first three years of the national Energy Sector Strategic Plan ESSP 2018-2024.

1.5. Layout of the dissertation

The rest of this research is organized as follows. Chapter 2 covers the literature review and briefly analyses the ideas of other relevant researchers on similar topics. Chapter 3 describes the used data and methodology. Chapter 4 provides and discusses the research results, while Chapter 5 deals with the conclusion and recommendations.

CHAPTER TWO: LITERATURE REVIEW

Literature review discusses and analyses the ideas of other researchers on similar topics. The majority of previous researchers have focussed their interest on assessing the impacts of power outages on peoples' welfare, firms' productivity, and the development of various sectors in a country. Few researchers have tried to assess the impacts of different policy interventions being implemented by countries around the world to ensure more reliable power systems.

2.1. Social-economic impacts of power outages

Power outages affect different aspects of people's life. For example, activities like washing clothes, vacuum cleaning or ironing can be rescheduled due to power interruptions. If an interruption occurs during a favourite radio or TV program, the loss becomes more disturbing as you cannot postpone the program. The food in your fridge or freezer can spoil after long time power outages. An unplanned shutdown of computers due to power outages may result in a huge loss of data. Following online courses and submission of online homework may be impossible if there is a power outage. Prolonged outages affect traffic lights and public transport, such as electric vehicles, trams and trains. For people with health problems in hospitals, even short-time power outages can be deadly due to lack of oxygen, etc. Vegetation requiring specific levels of temperature to survive cannot withstand long time power outages. Non-functioning street lights can increase robbery rates and put people's lives in danger (Martin , 2013). The study by (Hachimenum, 2015), analyses the impacts of power outages on the social-economic life of rural households in the Niger Delta region of Nigeria. The results reveal that increased power outages have resulted in stunted economic growth, reduced leisure time, and increased criminality and insecurity.

Power outages do not only affect people's routine living styles but also their business. As stated in the previous pages; power outages may result in huge monetary loss for individuals, enterprises and countries in general. Some researchers have tried to assess the impacts of power outages on firms' productivity. (Moyo, 2012), studied the impacts of power outages on Nigerian manufacturing firms. He found that power outages variables, which were measured by considering the number of hours per day without power and the percentage of the production lost due to power outages, had negative and significant effects on the firms' productivity, especially on small firms. According to (Matthew, Robert, & Giovani, 2018), the poor state of the electricity network, leading to increased power outages in many African cities, constitute the main hurdle for firms. They revealed that the issue of increased power outages in this region has pushed firms to purchase backup power generators, and this imposed additional investment and operational costs on these firms. The study estimated the cost of power interruptions across sub-Saharan Africa to be as much as 2.1% of GDP, and the total sales of African firms to be 4.9% lower than they would be if their electricity supply was reliable. In addition, they suggested that reducing the average hours of power outages to 118 hours a year, the lowest of all African countries could result in an increase in sales of 85.1% for all firms, rising to a 117.4% increase for firms without back-up generators. (Lamessa, 2018), also confirmed that, poor electricity supply increases the firms' production costs, and affects their competitiveness. According to his study, the more the frequency and duration of power outages, the more the firms will resort to alternative electricity supply means, and that may lead to reduced product quality, production stoppages and delays in service delivery. He added that poor supply of electricity could also affect investment decisions and firm location, which also has a negative cumulative effect on the firm's growth. His study examined the characteristics of power outages in Ethiopia, their economic cost and the firms' behaviours to respond to them using the translog cost function. The findings also showed that firms in Ethiopia preferred to alleviate the cost of power outages by installing self-generators. (Lassana & Abdoulaye, 2013), used the generalized linear model (GLM) to assess the impacts of power outages on the productivity of Small and Medium Enterprises (SMEs) in Senegal. This study analysed the productivity of the SMEs, measured as their cost efficiency, against three measures of quality of electricity service namely the number and duration of power outages, and a dummy that was created to measure whether electricity is a major concern for the firm. The study revealed that power outages duration had a positive and significant effect on their cost efficiency, while the number of power outages and the created dummy did not have a significant effect on the firms' cost efficiency. The study also revealed that firms had adopted various strategies to mitigate the effects of these power outages, such as shifting their staff to activities that do not require electricity when there is a power outage, shifting their production activities in time where electricity is available and investing in back-up power generators.

On the other hand; other researchers have tried to investigate the economic cost of power outages on people's welfare expressed as people's willingness to pay for a reliable power supply. For example; (Tensay , 2020) by using the generalized propensity and stated preference methods, he revealed that urban household with electricity connection in Ethiopia had to pay an amount of US$14.8 million per month, as a cost of various actions taken to mitigate the consequences of increased power outages. The same results have estimated the households' willingness to pay for improved electricity supply at US$6.2 million per month, in addition to the regular electricity bill. The study by (Aygul & Glenn , 2015), revealed that residential households in Cyprus were willing to incur 13.8% extra money in their electricity bills, to avoid the cost of power outages. The same study affirms that improved reliability of electricity supply would result in a benefit of US$35.6 million for the residential sector. A study that was conducted on 950 households in the Cape Coast Metropolitan Area in Ghana, confirmed that households were ready to pay 44% (US$3.42) of their electricity bill, as an extra cost to improve electricity services (Francis & Christian , Kyeremech, 2016).

The increasing importance of electricity supply reliability has been pushing countries around the world, to invest more in the power sector. Countries have set different policy targets, the regulatory framework was reviewed and huge amounts of budgets were availed to upgrade the aged systems and construct new power infrastructures. All these because countries around the world, especially the developing countries, believe that these reliability issues are mainly arising from aged power systems' infrastructures, poor design and lack of modern smart grid technologies (World bank, 2011). In addition, it should be remembered that overinvestment in the reliability of the power supply may lead to too high costs for society. For this reason, countries must optimally analyse these investments, to avoid the associated risks (Karin , 2011).

The researches on the impacts of these investments are still limited. The available researches mainly discuss the benefits of upgrading aged power infrastructures and deploying smart grid technologies such as; optimized operation and control of power systems, improved quality of service, increased efficiency and reliability (Yazhou , Chen-Ching , & Yin Xu, 2016). Few authors have dedicated their research to assessing the impacts of these investments. The study by (Shawn , 2016) did not provide a direct correlation between the financing of smart grids and the reliability of US power systems, due to the lack of all necessary data. However, he claimed that the number and duration of power outages and the magnitude of power losses had decreased, while the large blackouts continued to be rare as the country increased its investment in smart grid technologies.

From the above discussions; it is obvious that the majority of existing studies have focussed at investigating the social-economic impacts of power outages, and it is clear that there are still limited studies on the various policy measures implemented by countries around the world to mitigate the issues of power outages in their respective power systems. The main contribution of this research is that; it adds to the increasing growing interest in evaluating the causal impact of public policy interventions such as electrical power system reliability improvement related policies.

CHAPTER THREE: METHODOLOGY

3.1. Data and descriptive statistics

The main data of this research is administrative data on power outages across various distribution feeders in the country gathered from the Energy Utility Corporation Limited (EUCL), matched together with other information gathered from Rwanda Utilities Regulatory Authority. These data cover the period of January 2016 to October 2019 and comprise the daily information on the number, duration, type, and causes of power outages per each distribution feeder. They also provide information on the feeder's voltage level, the substation form which the feeder is connected, the feeder's district location and the hub in which it is located, and areas that were affected by these power outages. The second data comprise the list of the national power system's reliability improvement projects, commissioned during the period of study, and the names of distribution feeders that benefited from the commissioning of these projects. By matching the two datasets, on monthly basis, the final data consists of 24,031observations. Figure 3 shows the distribution of power outages in Rwanda during the period of study;

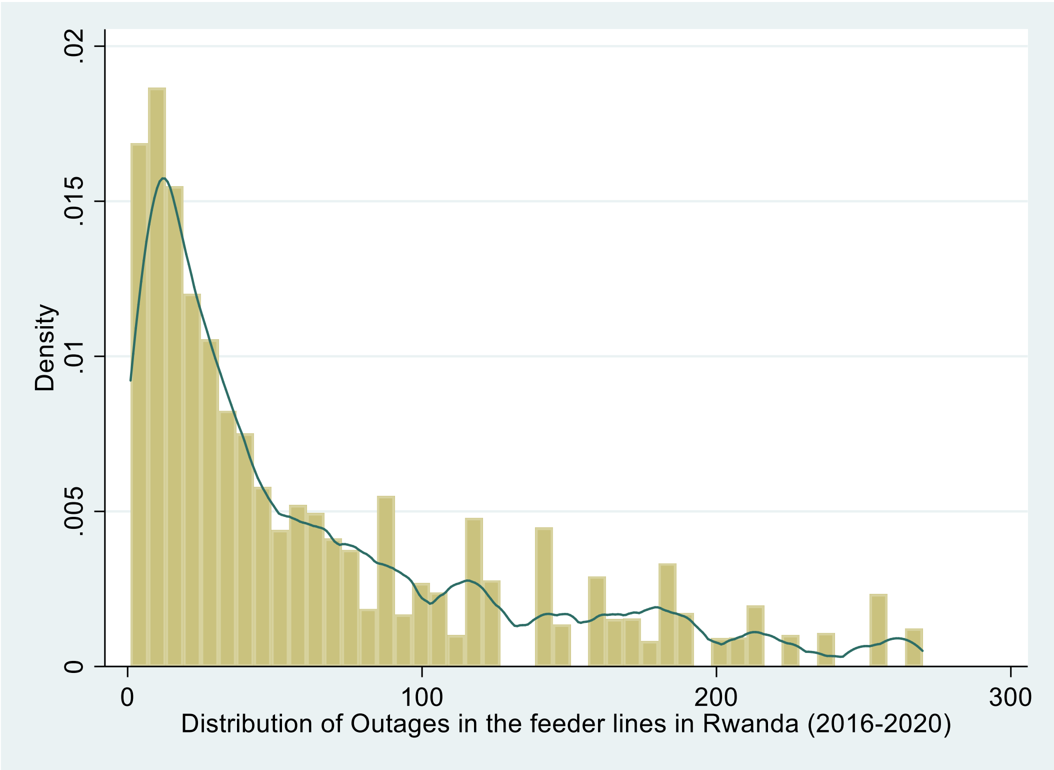

Figure 3: Distribution of power outages in Rwanda

Source: EUCL data

3.2. Empirical strategy

A quasi-experimental research using the difference in difference technique is used in this research. Difference in differences is a technique used in econometrics to evaluate and calculate the effect of a treatment or a program on individuals with the same characteristics. It attempts to assess the impacts of a sudden change in economic environment, policy, or general treatment on a group of individuals. The standard difference-in-differences technique has two periods, "pre" and "post", and two groups "treatment" and "control". The treatment group is the group subjected to the change while the control group is a group whose characteristics are similar to the treatment group but not subjected to the change. When the DiD is used, the effect of a program or a policy intervention (treatment) on outcomes is obtained as the pre-post differences in the outcome variables between treatment and control groups (Andrew , 2018). Difference in differences employs the outcome on the control group to estimate what would have happened to the treatment group had the treatment not occurred. The impact of the treatment is then measured using the difference in outcomes between the treatment and control groups post treatment (Angrist & Pischke, 2008).

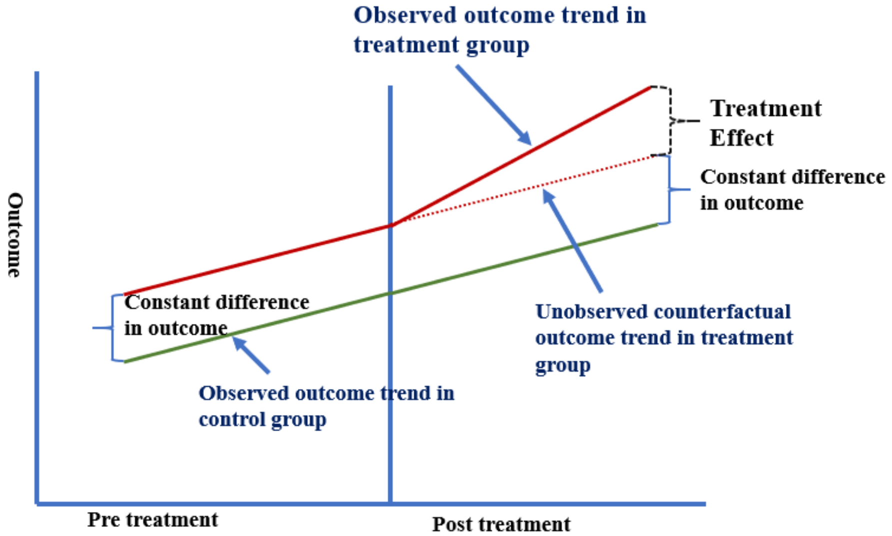

Figure 4. Difference-in-Difference estimation, graphical explanation

This study does not use the pre-post comparison between the beneficiary and non-beneficiary feeders, as this is unlikely to measure the causal effect of the program. However, it compares the changes in power outages' duration and frequency before and after the intervention, and controls for other external causes that may correlate with these changes.

To identify the causal impact of the program, the study exploits the plausibly exogenous variation in power distribution feeders upgrading and random power blackouts, to measure if there have been changes in power outages duration and frequency. Note that, interventions on different feeders did not occur at the same time, and some of the feeders were even subjected to more than one intervention during the study period. This creates variations in the periods from when feeders have experienced changes in power outage rates as the results of these interventions. It also creates variations in the number of rounds various feeders have incurred interventions.

Using the plausibly exogenous variations in the timing of various power outages, the following baseline model was estimated:

$$y_{frt} = \alpha + \beta FUP_{frt} + \varepsilon_{frt} \quad (1)$$

The coefficient α represents the feeder lines' fixed effects and absorbs all time-invariant differences across feeder lines that may be correlated with changes in power outages' duration and frequency. Y_{frt} is the vector of outcomes, for instance, the number of power outages on the feeder *f*, located in the district *r* in month *t*, and FUP_{frt}, which is the variable of interest, stands for distribution feeder upgrading/rehabilitation policy intervention at feeder *f*, located in the district *r* implemented at given time *t*.

The FUP_{frt} represents the various investments made by the Rwandan government, to address the reliability issues of the national power systems. It covers all the investments made in the power system sector including; the upgrade of existing power infrastructures and the construction of new power infrastructures as shown in annex 1. It is important to remember that; these investments were not done at the same time, at different feeders during the research period. In addition, as the power system is interconnected, it is possible that an investment on one feeder could affect other feeders, mainly the neighbouring ones, and consequently the entire systems. For this the reason, there are some feeders that got interventions more than one time during the research period, due to investments made in different times at their neighbouring feeders. FUP_{frt} does not stand for the amount that were invested to improve the reliability of a given feeder but it represents the commissioning dates of the various projects that were targeting the improvement of the reliability of those specific feeders.

The study also controls for other variables in this study and could have affected the changes in power outages' duration and frequency across different feeder lines. In this respect, the following equation (2) was also estimated:

$$y_{frt} = \alpha + \beta FUP_{frt} + \mu X_{rt} + \eta_f + \sigma_r + \lambda_t + \sigma_r * \lambda_t + \varepsilon_{irt} \quad (2)$$

Where *Xrt* is the vector of controls, including the feeder's location and other dummies. η_f, σ_r, λ_t, represent feeder lines, districts and time of policy fixed effects. While $\sigma_r * \lambda_t$ is the interaction between feeder lines and months' fixed effects.

In addition to this, the study exploits the plausibly exogenous variation in the spread of the covid-19 pandemic and its prevention measures, to measure if there have been changes in power outages duration and frequency across various feeder lines due to covid-19 pandemic. In this respect, the following equation (3) was estimated:

$$y_{frt} = \alpha + \beta FUP_{frt} + \varphi Covid_{rt} + \mu X_{rt} + \eta_f + \sigma_r + \lambda_t + \sigma_r * \lambda_t + \varepsilon_{irt} \quad (3)$$

Where $Covid_{rt}$ is the vector of control for the effect Covid-19 pandemic including the feeder location and other dummies.

CHAPTER FOUR: RESULTS AND DISCUSSIONS

4.1. Impact of FUP on power supply reliability

We start by showing the impact of distribution feeders upgrading policy on the reliability of power supply in table 1, by using the baseline model, equation 1. The results show that the feeder lines upgrading policy has an impact on power supply reliability, which is measured in terms of power outages' durations and frequencies.

Table 1: Baseline model for the Impact of FUP on electricity supply reliability

Variables	(1)	(2)	(3)	(4)
Feeder-line upgrading policy (FUP)	-0.160*	-4.437*	-0.357	-16.600
	(0.083)	(2.247)	(0.307)	(20.877)
Constant	2.245***	16.789***	4.522***	75.895***
	(0.079)	(2.270)	(0.212)	(15.263)
Observations	24,031	24,031	24,031	24,031
Mean of Outcomes	2.1470	14.519	4.323	62.662
R-squared	0.003	0.002	0.022	0.014

Notes: In the first column, we report the log of Outage Durations expressed in minutes while the second column contains the Outage Durations expressed in levels. The third column gives the log of Outage Frequencies while the last column indicates the Outage frequencies in levels. The frequencies represent the number of times the outages occurred at a given feeder-line per month between January 2016 and September 2020. The robust standard errors are clustered at Feeder-lines and they are reported in parentheses, and finally *** p<0.01, ** p<0.05, * p<0.1.

4.2. Heterogeneity effect of FUP on power supply reliability with controls

Firstly, we examine the impact of feeder lines upgrading policy on power supply reliability after controlling for the districts, cause of the outage and policy rounds fixed effects, and by alternating the month and feeder line per month fixed effects. We use the results of equation 2 as presented in table 2. The results show that the feeder line upgrading policy reduced the duration of power outages by 0.193 minutes per month (column 2). The fact that the impact of the policy intervention on the duration of power outages becomes significant after controlling for feeder line by month specific contemporaneous shocks; provides evidence that, there are other unobserved variables, which also had contributed to the reduction of power outages duration across various feeder lines in different months. And these include but not limited to; the various measures taken by the national electric utility company to ensure continuity of service delivery such as; the deployment of permanent maintenance teams that receive and resolve customers' queries for 24 hours, 7 days per week, setup of toll-free number and development of online communication platforms and social media channels to allow easy communication with the customers.

Besides, the same results show that the feeder line upgrading policy has a negative and statistically significant effect on power outage frequencies. They show that the policy reduced the power outages frequencies by 0.606 times per month (column 3), and the effect decreases slightly to 0.594 times per month and becomes more statistically significant if we control for feeder line per month specific contemporaneous shocks (column 4). This also shows that there are other unobserved variables that contributed to the reduction of power outage frequency, and this may be linked to the investments made in the power sector, especially on the electricity generation side. Note that during the last five years, the country has commissioned a notable number of new power plants; and this increased the available generation capacity and reserve margin. Remember that, a deficit in power generation constitutes one of the major causes of power outages in power systems.

Table 2: Heterogeneity effect of FUP on electricity supply reliability with fixed effects

Variables	(1)	(2)	(3)	(4)
Feeder-line upgrading policy (FUP)	-0.136	-0.193*	-0.606***	-0.594**
	(0.097)	(0.108)	(0.209)	(0.220)
Constant	2.257***	2.278***	4.617***	4.612***
	(0.042)	(0.040)	(0.102)	(0.081)
Observations	22,834	22,832	22,834	22,832
R-squared	0.090	0.152	0.516	0.703
district FE	YES	YES	YES	YES
Cause of Outage FE	YES	YES	YES	YES
Policy rounds FE	YES	YES	YES	YES
Month FE	YES	NO	YES	NO
Feeder line-by-Month FE	NO	YES	NO	YES

Notes: In the first and second columns, we report the log of Outage Durations expressed in minutes while the third and fourth columns contain the log of Outage Frequencies. The Outage frequencies represent the number of times the outages occurred at a given feeder-line per month between January 2016 and September 2020. The robust standard errors are clustered at Feeder-lines and they are reported in parentheses, and finally *** p<0.01, ** p<0.05, * p<0.1.

The power distribution feeder lines on which this study is concerned, are spread across different locations in the country. Some of them are located in urban areas, and others are located in semi-urban and rural areas. In addition to this, to ensure the balance between the generation and demand while avoiding entire system blackouts; the National Electric Control Centre (NECC) has adopted an automatic Under Frequency Load Shedding (UFLS) scheme, where some feeders were set to be more sensitive to power outages than others. And the type of supplied load and their location are among the criteria to be observed before setting a given feeder line to an automatic Under Frequency Load Shedding scheme. For example, all feeders supplying national hospitals and other areas like airports are set to be less sensitive to power outages than others. This is one of the reasons that we have to examine the impacts of feeder line upgrading policy after omitting the effects of all unobserved variables relating to the location of various feeder lines. For this, we use the results of equation 2 as presented in table 3. The results show that the feeder line upgrading policy has a negative impact on the duration of power outages, and the effect remains negative and becomes statistically significant if we control for feeder line by month fixed effects (column 2). They also show that the same policy had a negative and statistically significant effect on the frequency of power outages, and the effect increases if we keep the same control as previous. In other words, the feeder line upgrading policy reduces the duration and frequency of power outages by 0.193 minutes (column 2) and 0.594 times (column 4) per month respectively, if we control for feeder line by month fixed effects. These results show that the effects of other unobserved variables related to the location of various feeders are not much as we expect if we compare these results to those of table 2.

Besides, the results show that the feeder lines upgrading policy reduced the duration and increased the frequency of unplanned power outages, as compared to those of planned power outages. To understand this; we first need to remember that planned power outages were nothing else but planned maintenance works, which were mainly arising from the reason that the feeder lines were aged and overloaded. The age of these feeder lines increased also their probability to undergo frequent and long-duration maintenance works, where the maintenance teams had to spend a long period to solve the issues. It is then obvious that after upgrading the feeder lines, this probability had reduced; because it usually takes a shorter time to maintain new systems than aged systems, and the newly upgraded systems normally have a lower probability to incur frequent and long-duration planned works. This also justifies why the frequency of planned power outages reduced as compared to that of unplanned power outages.

Table 3: Heterogeneity effect of FUP on electricity supply reliability with control

Variables	(1)	(2)	(3)	(4)
Feeder-line upgrading policy (FUP)	-0.118	-0.193*	-0.564**	-0.594**
	(0.081)	(0.108)	(0.212)	(0.220)
Unplanned Outages (yes=1)	-2.022***	-1.991***	0.691***	0.509***
	(0.168)	(0.160)	(0.123)	(0.091)
Constant	4.250***	4.247***	3.918***	4.109***
	(0.159)	(0.167)	(0.143)	(0.131)
Observations	22,834	22,832	22,834	22,832
R-squared	0.082	0.152	0.462	0.703
District FE	YES	YES	YES	YES
Location FE	YES	YES	YES	YES
Month FE	YES	NO	YES	NO
Feeder line-by-Month FE	NO	YES	NO	YES

Notes: In the first and second columns, we report the log of Outage Durations expressed in minutes while the third and fourth columns contain the log of Outage Frequencies. The Outage frequencies represent the number of times the outages occurred at a given feeder-line per month between January 2016 and September 2020. The robust standard errors are clustered at Feeder-lines and they are reported in parentheses, and finally *** p<0.01, ** p<0.05, * p<0.1.

4.3. Effects of covid-19 pandemic

In this section, we use the results of equation (3) as presented in Table 4, to control for the impacts of covid-19 on feeder line outages. The theory of change between covid-19 pandemic and the power outages occurrence frequency and duration is that the pandemic reduced the electricity demand and therefore reduced the rates and duration of power outages mainly arising from system overloading. However, the results in table 4 show that the pandemic has increased the duration of power outages by 1.119 minutes per month (column 1), and the effect reduces to 1.060 minutes (column 2) and remains statistically significant if we control for feeder line by month specific contemporaneous shocks. This can be explained as follow; few days after the identification of the first case of the Covid-19 pandemic, Rwanda announced the country's first total lockdown. People were forced to work from home, and the majority of large consumers of electricity such as; public institutions, industries, supermarkets and hotels have remained inoperative for a long time. This demand reduction made a big difference between the power that circulated in the transmission lines and that for which those lines were designed. These power lines began to behave like capacitors, which increased the level of reactive power in the system, also resulting in increased frequency instability as power plants tended to run faster to overcome the stress, while system operators had to keep the frequency constant. Under these conditions, if a given feeder were to experience a power outage, it would take longer to restore power due to the above-mentioned frequency instability. In other words, the system operator first had to adjust the frequency of the disconnected feed to that of the entire system, before reconnecting the disconnected feed. A process that normally takes longer. This justifies the reason why the pandemic has increased the duration of power cuts.

Moreover, the results show that the pandemic had reduced the frequency of power outages by 1.41 (column 3) times per month, and the effect reduces to 1.248 (column 4) and remains statistically significant if we control for feeder line by month specific contemporaneous shocks. The fact that people were working from home, which in return increased their sensitivity to power outages, and the availability of toll-free number and other communication channels, which helped the customers to promptly raise the complaints, can be listed among the possible causes of the reduction in the frequency of power outages by the pandemic.

Table 4: Heterogeneity effect of FUP on electricity supply reliability with controls

Variables	(1)	(2)	(3)	(4)
Feeder-line upgrading policy (FUP)	-0.208**	-0.276***	-0.451*	-0.496**
	(0.076)	(0.099)	(0.221)	(0.229)
Unplanned Outages (yes=1)	-1.984***	-1.958***	0.643***	0.470***
	(0.168)	(0.161)	(0.120)	(0.091)
Covid-19 event (yes=1)	1.119***	1.060***	-1.410***	-1.248***
	(0.157)	(0.161)	(0.149)	(0.153)
Constant	4.213***	4.215***	3.963***	4.146***
	(0.157)	(0.164)	(0.141)	(0.131)
Observations	22,834	22,832	22,834	22,832
Mean Values of the Outcomes	2.147		4.326	
R-squared	0.099	0.167	0.497	0.729
District feeder line FE	YES	YES	YES	YES
Location (rural, urban and semi-urban) FE	YES	YES	YES	YES
Month of the Feeder Upgrade policy FE	YES	NO	YES	NO
Feeder line-by-Month FE	NO	YES	NO	YES

Notes: In the first and second columns, we report the log of Outage Durations expressed in minutes while the third and fourth columns contain the log of Outage Frequencies. The Outage frequencies represent the number of times the outages occurred at a given feeder-line per month between January 2016 and September 2020. The robust standard errors are clustered at Feeder-lines and they are reported in parentheses, and finally *** p<0.01, ** p<0.05, * p<0.1.

CHAPTER FIVE: CONCLUSION AND POLICY IMPLICATIONS

The power sector in many developing countries is still facing stability and reliability issues, which include but are not limited to increased power outages in both the duration and occurrence frequency. The principal causes of these power outages are related to generation deficit vis-à-vis of the increasing demand, lack of adequate protection, control and monitoring systems, and ageing infrastructures, etc. To address these issues, the Rwandan government decided to direct more investment in the upgrading and rehabilitation of the main power distribution lines across the country. These include the construction of new power substations, especially those linking high voltage transmission and medium voltage distribution lines, and new feeder lines, and the upgrading and rehabilitation of existing power substations and feeder lines.

This research aimed to evaluate the impact of the upgrade and rehabilitation of the main power distribution feeders on the reliability of the national power system, using administrative data on power outages durations and frequencies across various feeder lines in Rwanda. The analysis revealed that this policy intervention had a positive impact on the power supply reliability, which is expressed in terms of outages duration and frequency across feeder lines. The estimations show that the upgrade of main power distribution feeders across the country has reduced the duration and frequency of power outages. Interestingly, the results show that the impact becomes more significant as we control for the effects of unobserved variables across different variables of the study. This shows that, despite the effects of other unobserved variables that may be correlated with changes in power outages across various feeder lines, mainly related to their location (rural, urban and suburban) and changes in seasonality (dry and rainy season) within different months of the year, the impact of the policy remains evident. Hence, the results provide evidence that upgrading /rehabilitating power systems infrastructures is one of the mechanisms to improve their reliability. The study also shows that there are other unobserved variables, mainly related to location and changes in season, that are also affecting the reliability of the Rwandan power system. Therefore, it is recommended that the government should look for other means of alleviating these types of power outages. The deployment of modern smart grid technologies should among the best options. It is suggested that future researchers would not only focus on the improvement of the findings of this research but also on investigating the social-economic impacts of power outages on peoples' welfare, companies and firms, especially in Rwanda.

Further, the study investigated the impact of the covid-19 pandemic on the reliability of the power supply, and the results showed that it had a positive impact on the duration of power outages, and a negative impact on the frequency of power outages.

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ANNEX 1: List of commissioned feeders and respective beneficial feeders

#	Project name	Beneficial feeders	Commissioning date (Month/Year)
1	Installation of 2 transformers at Mont Kigali	Kanazi	1/12/2018
		Kiyumba	
		Nyamirambo	
		Nyarurama	
2	110 kV line Jabana-Mont Kigali-Gahanga	D.Welle	1/12/2018
		Kigali	
		Rutongo	
		Sucrerie	
		Utexerwa	
		Master Steel	
		Pylon 20	
3	Construction of NZOVE substation	Abattoir	1/3/2019
		Nzove	
4	Design, Supply, Install and commissioning of 15KV substation equipment (11 MV Switching Cabins)	Birembo	30/08/2020
		Free zone 1	
		Gikondo Haut	
		Gasogi	
		Kigali North	
		Kigali South	
		Kimihurura	
		Inyange	
		Kabuga	
		Kbgbg/Nyarutarama	
		Kibagabaga/Remera	

		Kimironko	
		Kinyinya	
		Kanombe	
5	Construction of new Ndera SS	Birembo	
		Free zone 1	
		Gikomero	1/11/2018
6	Murindi Ring Main Unit (RMU) Switching Station	Kabuga	1/11/2018
		Kanombe	
		Inyange	
		Gasogi	
7	Kabuga RMU Switching Station	Kabuga	1/11/2018
		Kanombe	
		Gasogi	
8	Installation of Capacitor Banks	D.Welle	30/09/2019
		Kigali	
		Rutongo	
		Sucreire	
		Utexerwa	
		Gikondo Haut	
		Gasogi	
		Kigali North	
		Kigali South	
		Kimihurura	
		Nyarurama	
		Kbgbg/Nyarutarama	
		Kibagabaga/Remera	
		Kimironko	
		Kinyinya	

9	Design, Supply, Install and commissioning of 15KV substation equipment (6 MV Switching Cabins)	Birembo	30/10/2018
		Free zone 1	
		Gikondo Haut	
		Gasogi	
		Kigali North	
		Kigali South	
		Kimihurura	
		Inyange	
		Kabuga	
		Kanombe	
10	Construction of Rulindo-Musha-Gabiro 110kV Lines and associated substations	Base	1/10/2018
		Byumba	
		Gasiza	
		Musasa	
		Karenge	
		Redemi	
		Rwamagana	
		Kiziguro	
		Ngarama	
		Nyagatare	
11	Rehabilitation of Gifurwe substation and associated Feeders	Gakenke	1/3/2019
		Kirambo	
		Ntaruka	
12	Upgrade of Mukungwa 6.6/30kV transformer	Camp Belge	
		Gaseke	
		Janja	
		REMERA	5/5/2018

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