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Interaction between Armed Conflicts and Energy Prices in Colombia

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ABSTRACT

This study investigates the complex relationship between armed conflicts and electricity prices in Colombia, considering the effects of climatic variables. Given the strategic importance of energy resources for economic and social development, understanding how conflicts influence energy prices is crucial. Using Generalized Additive Models (GAM) and Distributed Lag Non-linear Models (DLNM), we analyze the immediate and delayed impacts of battles, deaths, solar radiation, and precipitation on electricity prices. Our findings reveal that battles significantly increase electricity prices contemporaneously, highlighting the vulnerability of Colombia's electrical infrastructure. The DLNM analysis shows that these effects can reemerge weeks after the initial conflict, with significant price increases particularly between weeks 4-6 and 7-8. Additionally, climatic variables like solar radiation and precipitation exhibit non-linear effects on electricity prices, where moderate increases in these variables reduce prices, but extreme conditions elevate them. These results underscore the need for integrated strategies that address both socio-political and climatic factors to enhance energy resilience. Our study provides valuable insights for policymakers and energy sector stakeholders, emphasizing the importance of mitigating conflict impacts and adapting to climatic variability to ensure a stable and sustainable electricity supply in Colombia.

Keywords: Armed Conflicts; Electricity Prices; Colombia; Climatic Variables; Generalized Additive Models; Distributed Lag Non-Linear Models; Energy Resilience
JEL Classifications: O13; Q34; Q43.

1. INTRODUCTION

Understanding the interaction between armed conflicts and energy prices in developing countries is crucial due to the complexity of these phenomena. The connections between energy and conflict can be approached from various perspectives, whether geopolitical, environmental, or economic (Månsson, 2014). This relationship is essential because energy resources are strategic for economic and social development (Wen et al., 2018; 2019), as well as a determinant of global economic growth (Chen and Wu, 2017; Chen and Zhu, 2021).

Given the importance of energy supply for economic progress, the stability of energy prices has acquired critical relevance, attracting special attention from multiple countries. However, the scarcity of energy resources, their strategic significance, and the geographical dislocation between supply and demand contribute to making energy prices highly susceptible to various conflicts (Qin et al., 2020). Often, the relationship between energy prices or energy systems and armed conflicts is analyzed by focusing on a single factor or a single energy carrier, such as oil, and at a specific level of analysis (international, national, or local) (Månsson, 2014), which can limit our understanding of the underlying dynamics.

In the Colombian context, the relationship between conflicts and energy systems is particularly critical due to the interdependence between energy security and political and social stability (Beccue et al., 2018). According to Månsson (2014), conflicts can manifest in various ways concerning energy: they can be objectives, means, or even causes of conflicts. These conflicts present three levels of severity (violent, social instability, and political disputes), which modify the relationship between phenomena. This complex interaction poses significant challenges for energy management and policy in Colombia. Conflicts in the region can generate significant delays in the energy transition towards clean and sustainable sources. Political and social instability, as well as disputes over energy resources, can hinder the implementation of renewable energy projects, affecting the efficiency and sustainability of the energy transition and energy security.

Addressing these challenges is essential to ensure energy security and that the adoption of clean energy is effectively carried out, contributing to the country's sustainable development. Our research focuses on exploring how the presence of conflicts and their intensity, represented by variables such as the number of clashes and deaths, can influence energy prices in Colombia. Political and social dynamics can have a significant impact on energy security and price stability. This study aims to provide a deeper understanding of how these different levels of interaction between conflict and energy can affect energy prices in the country.

Our research employs an empirical approach that integrates Generalized Additive Models (GAM) and Distributed Lag Non-linear Models (DLNM) to analyze how battles and other conflict variables, along with climatic factors such as solar radiation and precipitation, influence electricity prices in Colombia. The results obtained through the GAM model reveal that battles, solar radiation, and precipitation are significant factors influencing electricity prices. Battles show an immediate positive effect, increasing contemporary electricity prices, highlighting the vulnerability of the Colombian electric system to armed conflicts.

The DLNM analysis allows for an in-depth exploration of the temporal and lagged effects of battles on electricity prices. It is observed that the effects of battles can re-emerge after a certain period, particularly between weeks 4 and 6, and again in weeks 7 and 8. This behavior suggests that cumulative damage and prolonged disruptions to electrical infrastructure have long-term repercussions on electricity costs. Furthermore, it is noted that the intensity of battles, not just their occurrence, is a crucial determinant of the increase in prices.

The relevance of this study is significant for both academics and professionals in the energy sector and public policy. Our findings are crucial for policymakers seeking to improve the resilience of the electrical system to armed conflicts and climatic variations. Additionally, the results are of interest to energy companies that need to plan and manage infrastructure effectively, minimizing risks and costs associated with socio-political instability. The detailed understanding of how conflicts and climatic conditions affect electricity prices is also valuable for researchers in economics and energy, providing a solid foundation for future studies and the formulation of operational strategies that ensure a more stable and sustainable electricity supply in Colombia.

The document is organized into several sections. The second section presents the relevant literature review. The third section details the methodology employed, including GAM and DLNM models. The fourth section shows the analysis results. Finally, the fifth section offers the conclusions and practical implications of the findings.

2. LITERATURE REVIEW

Understanding the complex interactions between armed conflicts and the energy market is a topic of growing importance in contemporary economic and geopolitical analysis (Dalby, 2002). The volatility of energy prices can significantly influence the economic and political stability of countries, affecting both producer and consumer economies. This instability can not only trigger or amplify armed conflicts but can also be a result of them (Ringim et al., 2022; Zhao et al., 2023). In regions with abundant energy resources, struggles for control of these resources tend to intensify, while in countries dependent on energy imports, sudden price increases can generate social and political tensions (Robert and Lennert, 2010).

The bidirectional and complex relationship between energy and armed conflicts demonstrates that energy prices can influence the emergence and escalation of conflicts, and in turn, armed conflicts can significantly impact energy prices and supply security. However, this relationship is complicated, and there is still no general consensus in the literature on the transmission mechanisms (Ciută, 2010). This literature review, based on the study's objective, focuses on the direction in which armed conflicts impact energy prices, presenting that different levels, types of severity, and transmission mechanisms may exist (Månsson, 2014).

The theoretical framework proposed by Månsson (2014) addresses these dynamics, pointing out that not only the presence of fossil fuels and their transportation routes affect the risk of conflicts, but also other aspects of the energy system and contextual conditions, such as social, economic, and political factors. Generally, this topic has been studied through multiple approaches. Realism highlights the competition system between states, where conflicts arise from power and security struggles (Lebow, 2010). Geopolitics, on the other hand, emphasizes the importance of geography and resources in explaining international conflicts (Cai and Wu, 2021; Muñoz et al., 2015). In the field of Political Economy, the debate centers on whether economic viability or political motives are the main cause of internal conflicts (Česnakas et al., 2016).

Types of armed conflict can generally be categorized into interstate and intrastate conflicts. Generally, an interstate conflict is considered an armed confrontation between two or more sovereign states, where the military forces of the involved countries face each other directly. On the other hand, an intrastate conflict is understood as a conflict that occurs within the borders of a single state, generally involving the government and one or more-armed factions outside the law. Although these types of conflict have similar characteristics, they differ in the type of actors involved (Rowe, 1999). Interstate conflicts involve state actors and their national armies, while intrastate conflicts usually involve a combination of state and non-state actors. Sometimes, the nature of these conflicts can be influenced by the characteristics of the region's energy system, as the control and access to energy resources can be both a cause and a strategic objective in armed disputes (Česnakas et al., 2016).

Regarding the different types of conflict severity, they can be classified into three main categories: Violent conflicts, political disputes, and social instability (Månsson, 2014). Violent conflicts include wars and other armed confrontations with human casualties. A notable example is the war between Russia and Ukraine, which has not only caused a humanitarian emergency but also profoundly destabilized the political, economic, and financial balance of Europe due to energy dependency (Manelli et al., 2024; Zhang et al., 2024). Political disputes are characterized by conflicts that manifest mainly through economic and political means rather than direct physical violence. These disputes can include economic sanctions, trade blockades, and other forms of political pressure (Rowe, 1999).

Social instability manifests through social unrest, mass protests, and internal armed conflicts, which can arise for various reasons, including discontent with government policies or economic conditions. These events, although generally less lethal than interstate wars, have a significant impact on a nation's social cohesion and stability (Martínez and Castillo, 2016). Internal armed conflicts (intrastate), such as the armed conflict in Colombia, involve multiple outlaw groups, which have had profound repercussions on the country's political and social stability. Additionally, they have significantly affected the infrastructure of strategic sectors, such as education and energy (Toft et al., 2010).

The energy sector can play multiple roles in armed conflicts, whether as a primary target, strategic means, or cause (Månsson, 2014). Conflicts can arise from actors; intentions to improve their energy security by securing control over parts of the system, making energy the central objective of the conflict (Kumhof and Muir, 2014). On the other hand, energy can be used as a strategic means to achieve non-energy objectives, whether economic or political, through sanctions thanks to its advantages in the energy market (Česnakas et al., 2016). Finally, energy can act as a secondary cause of conflict by destabilizing a society and contributing to conflict indirectly. The exploitation, production, or use of energy can generate tensions that can exacerbate existing conflicts (Sandoval et al., 2017).

The aforementioned mechanisms explain the interactions between energy systems and conflicts individually; however, it is important to note that, in certain cases, conflicts arise from the interaction of several of these mechanisms. In the context of the armed conflict in Colombia, it can be characterized as an intrastate conflict with a severity related to social instability. Finally, it historically shows mechanisms where the energy system has been used as a means and a cause of the armed conflict (Lordan-Perret et al., 2019; McNeish, 2017; Sandoval et al., 2017).

Just as the Colombian conflict has been analyzed from a political economy perspective considering the conflict as a means or cause of interaction with the energy sector, multiple international studies have investigated this relationship at different points in the economic cycle. The influence of regional conflicts on the price cycles of renewable and fossil energy based on the economic cycle of the energy sector has been studied (Maneejuk et al., 2024), showing the sensitivity of renewable and fossil energy prices to conflict events. Additionally, the relationship between economic uncertainty and price volatility in energy markets has been explored (Naeem et al., 2021; Ringim et al., 2022). These investigations highlight how events such as economic crises, regional conflicts, or the pandemic have significantly impacted the stability and behavior of energy prices, emphasizing the complexity of the factors influencing these markets and the importance of considering multidisciplinary approaches for their analysis and management.

The armed conflict in Colombia, lasting more than 60 years, has had various effects on the country's energy system. Destruction of infrastructure, disruption of transportation routes, and attacks on energy transmission towers have been observed (Martínez and Castillo, 2016), which could generate fluctuations in energy markets, increasing economic and social tensions. Additionally, it has been identified as a significant cause of conflict, especially due to the local abundance of resources and environmental degradation of non-renewable resources (Collier and Hoeffler, 2004). Despite the extent and complexity of the conflict, academic research addressing this relationship from an empirical approach in Colombia has been limited.

In developing countries, this issue has been addressed from various perspectives. For example, in Mexico, Colombia, and Bolivia, which are some of the main oil producers in Latin America, oil and gas theft has been documented as a phenomenon associated with the "resource curse" due to its use for drug production (Walsh, 2012). Additionally, pipeline sabotage and large-scale illegal oil extraction have become increasingly relevant problems. Terrorist groups, insurgents, and members of criminal organizations have demonstrated the capability and willingness to attack critical energy infrastructures (CEIs), which is a particularly significant challenge in post-conflict regions and weak states.

It has been shown that armed groups such as the Revolutionary Armed Forces of Colombia (FARC) and the National Liberation Army (ELN) increase their attacks on energy infrastructures before elections, increasing the probability of attacks on power transmission lines and substations by 34% (Lordan-Perret et al., 2019). Furthermore, a conflict-related indicator linked to mineral exploitation has been proposed, revealing that activities such as murder, displacement, and pollution are highly correlated with conflicts arising from resource extraction (Sandoval et al., 2017). Additionally, the idea that resource extraction can finance peace has been questioned; it is found that promoting the extractive sector in Colombia increases insecurities and human rights violations, instead of promoting justice and economic growth in the post-conflict period as has sometimes been proposed from government positions (McNeish, 2017).

Despite numerous studies addressing the issue of the relationship between conflict and the energy sector in developing countries, there is a notable gap in the literature regarding specific analyses related to energy prices being analyzed from political economy perspectives. This gap is evident in the case of Colombia, where most studies have focused on linear approach methodologies without considering other alternatives, which have gained popularity internationally due to their ability to handle the high volatility inherent in these problems. The application of non-linear methodologies would allow for a more detailed and precise analysis, thus providing a more comprehensive and robust understanding of the energy dynamics in contexts of high uncertainty and risk.

3. METHODOLOGY AND DATA

3.1. Generalized Additive Model – GAM

To explore the non-linear relationships between conflict variables and energy prices, we propose using a Generalized Additive Model (GAM). This method is particularly suitable for our study because it can better capture and predict outcomes where interactions are not linear (Rigby et al., 2005). Generalized additive models offer flexibility by allowing the relationship between the response and explanatory variables to adjust locally through smooth functions rather than fixed parametric equations (Capa et al., 2014). Unlike traditional parametric models, GAMs do not assume a constant equation for the relationship between variables. Instead, they estimate smooth functions that can vary across different ranges of data, providing a nuanced fit to the data (Hastie and Tibshirani, 1987).

In a GAM, the response variable (in this case, energy prices) is expressed as an additive combination of smooth functions of the predictor variables $X = (x_1, x_2, \cdots, x_p)$. This can be represented mathematically as:

$$(Y \mid X = (x_1, x_2, \cdots, x_p)) = \alpha + g_1(x_1) + \cdots + g_p(x_p) + \varepsilon \quad (1)$$

Here, $g_j(x_j)$ are smooth functions that capture the potentially complex and non-linear relationships between the predictors and the response variable. This flexibility is crucial for modeling the interactions between conflict indicators and energy prices. The estimation of these functions involves a combination of backfitting algorithms and likelihood maximization. The backfitting algorithm iteratively adjusts the smooth functions to best fit the data. The process can be summarized as follows:

1. Initialization: Start with initial estimates for the smooth functions $g_j(x_j)$.
2. Iteration:
   - For each predictor x_j, update the smooth function $g_j(x_j)$ by fitting a smoothing spline or another non-parametric smoother to the partial residuals $Y - \alpha - \sum_{k \neq j}^{p} g_k(x_k)$.
   - This step is repeated for all predictors, cycling through them multiple times until the estimates converge.
3. Convergence: The algorithm iterates until the changes in the smooth functions are smaller than a pre-specified tolerance level, indicating that the model has converged to an optimal fit.

This iterative procedure ensures that the model adapts to the unique patterns present in our dataset, making it particularly useful for understanding the impact of conflicts on energy prices in Colombia.

One of the key advantages of GAMs is their ability to model complex, non-linear relationships without assuming a specific functional form for the predictors. This flexibility allows for a more accurate representation of the underlying data structure, leading to better predictive performance (Hastie and Tibshirani, 2017). However, the use of smooth functions also introduces challenges. Interpreting the results can be more complex compared to traditional linear models, as the relationships are not captured by simple coefficients but by smooth curves. Visualization tools are often necessary to interpret the fitted smooth functions, which can complicate the analysis. GAM is a modern statistical technique that does not require compliance with the assumptions of parametric statistics and allows the fitting of statistical models in accordance with ecological theory (Katsanevakis and Maravelias, 2009).

3.2. Distributed Lag Non-linear Model – DLNM

To deeply analyze the relationship between the number of battles and electricity prices over time, a DLNM model was used. This model is suitable for capturing the delayed and non-linear effects of a predictor variable on a response variable. The DLNM allows us to evaluate how the effects of battles on electricity prices are distributed over different temporal lags. A DLNM combines the flexibility of generalized additive models (GAM) and time series models. The general specification of the DLNM model can be represented by the following formula:

$$Y_t = \alpha + \sum_{k=0}^{K} f_k\left(X_{t-k}\right) + \epsilon_t \quad (2)$$

Where, Y_t: Electricity price at time t. α: Model intercept. K: Maximum number of lags considered. $f_k(X_{t-k})$: Smoothing function that captures the effect of the variable X (battles) at time $t-k$. ϵ_t: Error term. The DLNM model allows for the analysis of not only the contemporary effects of battles on electricity prices but also how these effects develop and persist over time. This is particularly useful in contexts where the impacts of an event (such as a conflict) do not manifest immediately but have prolonged repercussions.

The DLNM approach was developed by Gasparrini and Armstrong (2013) to provide a flexible methodology that can handle both delayed and non-linear effects of predictors on a response. This model is implemented in the dlnm package in R, which facilitates its application to time series data (Gasparrini, 2011). The flexibility of the DLNM allows for the adjustment of non-parametric smoothing functions, such as splines, which are useful for capturing the complex relationships between predictor variables and the response. In this study, the DLNM was used to model the relationship between the number of battles and electricity prices, controlled for the other variables mentioned. Lags of up to 8 weeks were considered. The smoothing functions f_k were adjusted using cubic splines to capture non-linear relationships. The results of the DLNM model provide a detailed understanding of how battles affect electricity prices over time, revealing both immediate and cumulative effects.

3.3. Data

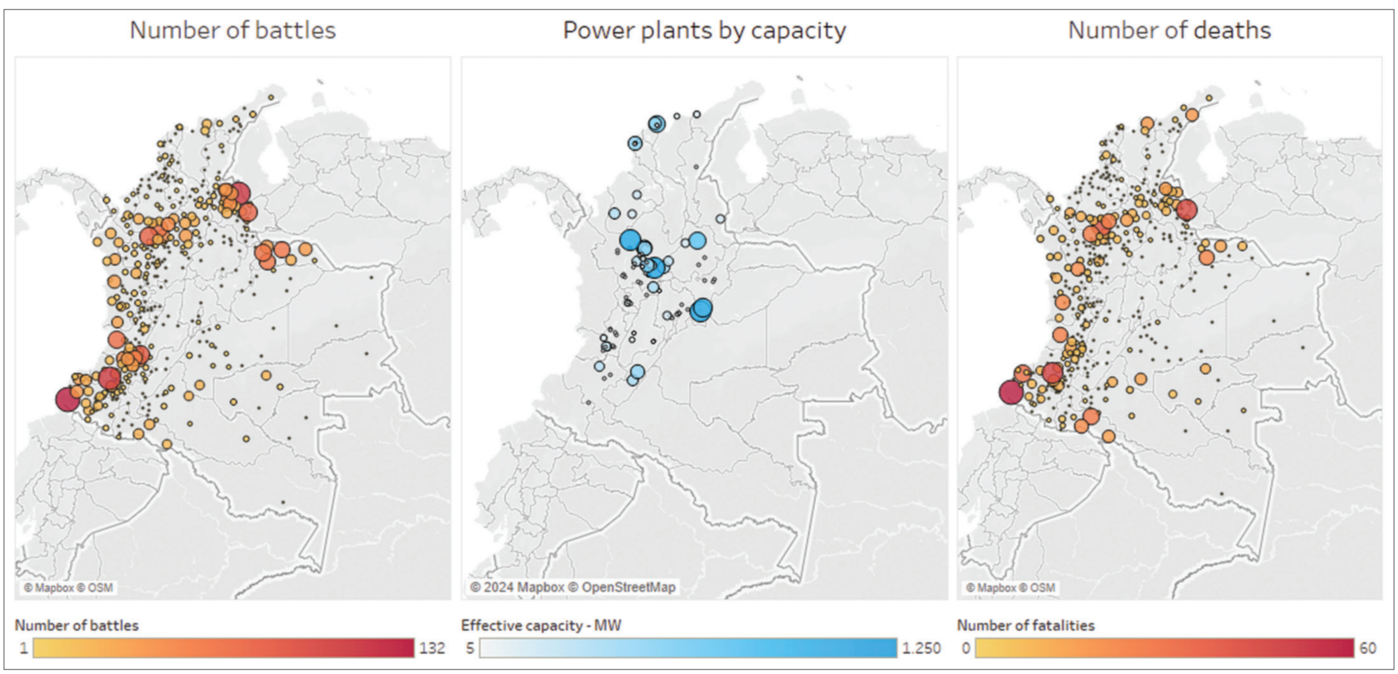
The data utilized in this study were sourced from ACLED for conflict variables, XM for energy prices, and NASA Power for climate data, spanning the period from 2018 to 2024. The conflict data, including information on deaths and battles, were sourced from the Armed Conflict Location & Event Data Project (ACLED). ACLED is a global organization who collect and analyze data on political violence and protest events worldwide. Their comprehensive data collection includes real-time information on locations, dates, actors, fatalities, and types of political violence and protest events. Energy price data were obtained from XM, a Colombian company that specializes in the management of real-time systems, administration of the wholesale energy market, and development of energy and information solutions and services. XM's responsibilities include planning, designing, optimizing, commissioning, coordinating operations, and managing transactional systems that involve the exchange of value-added information and markets for related goods and services. XM contributes to the sustainable development of Colombia by providing high-quality energy and facilitating the transformation of the electric sector through technology and knowledge development. Climate data, including precipitation, solar radiation, and wind speed, were downloaded using the NASAPOWER library in R. The NASA Power project offers global meteorological data derived from satellite observations and reanalysis models, essential for analyzing the impact of climatic variables on energy prices.

The integration of these diverse data sources enables a comprehensive analysis of the factors influencing electricity prices in Colombia. The conflict data from ACLED provide insight into the socio-political factors, while the energy price data from XM offer detailed information on the economic aspects. The climate data from NASA Power allow for the examination of environmental influences. Together, these datasets facilitate a robust analysis of how conflicts, climatic conditions, and market dynamics interact to affect electricity prices. The chosen time window from 2018 to 2024 is particularly relevant as it captures recent trends and significant events, including peaks in electricity prices, major conflicts, and notable climatic variations. This period allows for the assessment of both immediate and prolonged impacts of these variables on the energy market, providing a comprehensive understanding of the dynamic interplay between socio-political events, environmental factors, and economic outcomes in Colombia.

4. RESULTS AND DISCUSSION

This section presents the results of the empirical analysis on the relationship between armed conflicts and electricity prices in Colombia, also considering the influence of climatic variables. Figure 1 provides a geospatial representation of the conflict data and electricity generation capacity in the country. The results presented in this section are developed in two main parts: first, the immediate and delayed impact of the conflict and climatic variables on electricity prices is analyzed using a GAM model; and second, the temporal and cumulative effects of armed conflicts on electricity prices are examined using a DLNM model. This combination of approaches provides a comprehensive understanding of the factors influencing the variability of electricity prices in Colombia.

Figure 1: Geospatial distribution of battles, power plant capacity, and fatalities in Colombia



The maps show the number of battles (left), power plant capacity (center), and deaths (right) in Colombia. Colors range from orange to dark red for battles and deaths, and shades of blue for power plant capacity. This visualization highlights regions where conflicts overlap with critical power infrastructure, indicating areas at risk of electricity supply disruptions

4.1. Colombian Conflict

Figure 1 consists of three maps that show, from left to right, the number of battles, the capacity of power plants, and the number of deaths. In the first map, the geographical distribution of the number of battles is observed, with colored points ranging from orange to dark red, indicating from a lower to a higher number of battles. The second map illustrates the location and capacity of power plants, with circles of different sizes and shades of blue representing effective capacity in megawatts (MW). The third map shows the distribution of the number of deaths, using a color scale similar to the first map. These counts of deaths and battles are aggregated at the municipal level throughout the entire study period.

Identifying areas with the highest conflict (battles and deaths) and their overlap with the locations of power plants is crucial to understanding how conflict events can impact the generation and distribution of electricity in Colombia. Regions with a high incidence of battles and deaths, combined with the presence of critical electricity generation infrastructure, are particularly vulnerable to disruptions in the power supply. This geospatial analysis allows us to visualize areas where electrical infrastructure may be at greater risk due to conflict activity, providing a solid basis for planning mitigation and resilience strategies in the electric sector.

Table 1 presents the descriptive statistics of the studied variables: Electricity Price, Deaths, Battles, Precipitation, Solar Radiation, and Wind Speed. These statistics include the minimum value, first quartile, median, mean, standard deviation, third quartile, and maximum value.

In Figure 2, Panel A shows the evolution of electricity prices from 2018 to 2024. It can be seen that prices exhibit significant variations over time, with notable peaks at the end of 2022 and 2024. These peaks may be related to seasonal factors, extreme weather events, or demand increases due to conflicts. The mean price is 251.2 with a standard deviation of 195.5, indicating high variability. In Panel B, the number of battles and deaths in Colombia during the same period is shown. Battles (in orange) are more frequent than deaths (in red), and both variables show great fluctuation. The median number of battles is 11, and the median number of deaths is 3, indicating that while conflicts are common, deaths are less frequent. Peaks in battles may be correlated with increases in electricity prices observed in the first graph.

Panel C presents the amount of weekly precipitation in millimeters from 2018 to 2024, showing a pattern of high variability with significant peaks. The mean precipitation is 0.2 mm with a standard deviation of 0.3 mm. Precipitation peaks can affect hydroelectric generation, thus influencing electricity prices. In Panel D, solar radiation in W/m^2 over time is shown. A clear seasonal pattern with annual peaks is observed. Solar radiation has a mean of 12.1 W/m^2 and a standard deviation of 13.8. Solar energy generation is directly influenced by these patterns, affecting the electricity supply and possibly its price. Finally, in Panel E, wind speed in m/s is shown, which presents high variability with significantly oscillating values over time. Wind speed has a mean of 12.5 m/s and a standard deviation of 2.6. Like solar energy, wind energy is a renewable energy source that can influence the stability of the electricity supply.

The graphs and descriptive statistics provide a comprehensive view of the factors affecting electricity prices in Colombia. The variability in electricity prices can be influenced by both climatic factors (precipitation, solar radiation, wind speed) and socio-political factors (battles and deaths). Peaks in battles and precipitation coincide with increases in electricity prices, suggesting a relationship between these events and the instability of the electricity supply. On the other hand, solar radiation and wind speed show seasonal patterns that also contribute to the fluctuation in the supply of renewable energy, impacting electricity prices. These analyses highlight the importance of considering both climatic factors and conflicts in the planning and management of the electric system in Colombia.

4.2. Empirical Approach

4.2.1. Impact of conflict and climate on electricity prices

The Generalized Additive Model (GAM) developed to analyze electricity prices using various predictor variables provides valuable information about the factors affecting this price. A detailed summary of the GAM results is provided in table 2. Firstly, the intercept estimate is 251.20 with a standard error of 10.52. This coefficient is highly significant, indicating that the model has a significant baseline constant. This suggests that even without considering the effects of the predictor variables, there is a significant base price for electricity. The model explains approximately 13% of the variance in the response variable, which, although not very high, is understandable considering that energy prices themselves are influenced by a multitude of additional components, such as energy generation and distribution, which are beyond the scope of this study. Our primary objective is to capture the specific relationship between conflict and electricity prices, controlling for climatic variables.

Table 1: Descriptive statistics

Descriptive statistics	Electricity price	Deaths	Battles	Precipitation (mm)	Solar radiation (w/m^2)	Wind speed (m/s)
Min	67.6	0.0	2.0	0.0	0.0	5.9
1st Qu	117.2	1.0	7.0	0.0	0.0	10.6
Median	190.8	3.0	11.0	0.1	5.7	12.5
Mean	251.2	3.8	11.5	0.2	12.1	12.5
Standard deviation	195.5	3.8	5.6	0.3	13.8	2.6
3rd Qu	309.0	5.0	14.0	0.2	24.3	14.1
Max	1243.4	29.0	37.0	2.1	40.9	19.4

This table shows the minimum, first quartile, median, mean, standard deviation, third quartile, and maximum values of the variables: Electricity price, deaths, battles, precipitation, solar radiation, and wind speed

Figure 2: Temporal evolution and variability of climate and conflict variables (2018-2024.
Panel A (a) shows the variations in electricity prices, highlighting significant peaks at the end of 2022 and 2024. Panel b (b) Presents the frequency of battles and deaths in Colombia, indicating the relative frequency of both events. Panel C (c) Illustrates the variability of weekly precipitation, with significant peaks influencing hydroelectric generation. Panel d (d) Seasonal patterns of solar radiation, with annual peaks affecting solar energy generation. Panel e (e) Presents the variability of wind speed over time, highlighting its influence on wind energy generation

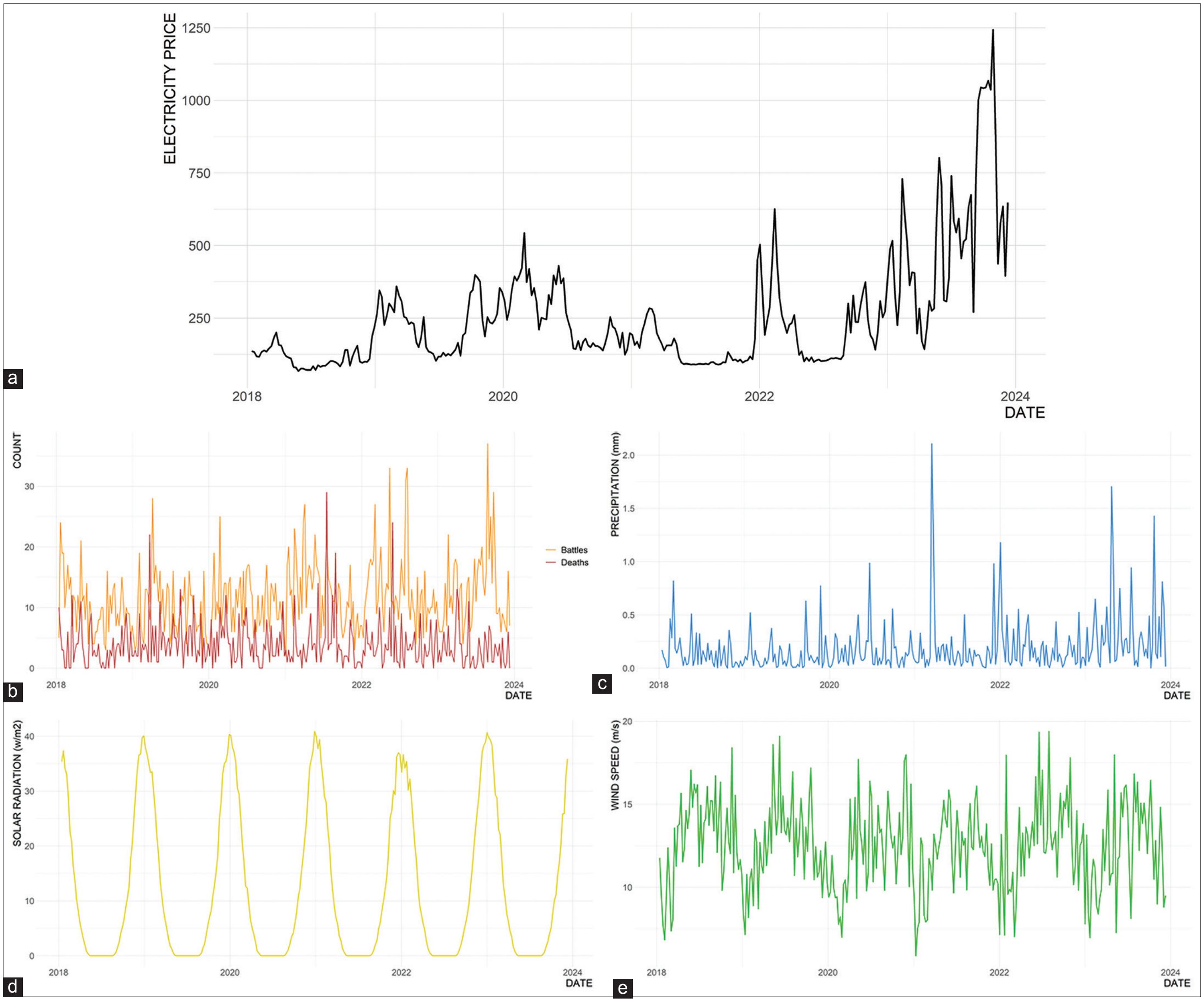


Table 2: Summary of the GAM results for electricity prices

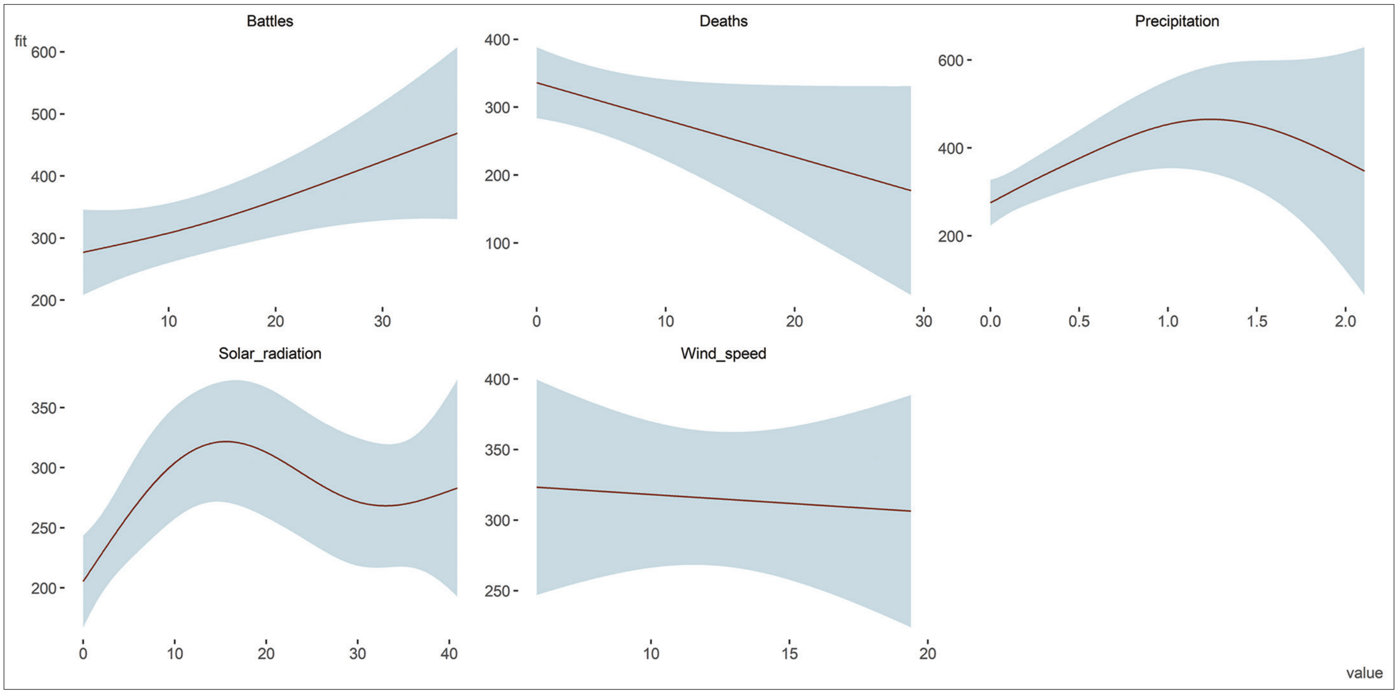
Parametric term	Estimate	Standard deviation	t-value	Pr(>|t|)
Intercept	251.2	10.52	23.88	<2e-16***
Smooth terms	**edf**	**Ref.df**	**F**	**P-value**
s (Deaths)	1	1	3.578	0.05953
s (Battles)	1.313	1.558	5.102	0.02905*
s (Wind speed)	1	1	0.071	0.78993
s (Solar radiation)	2.862	3.355	4.316	0.00492**
s (Precipitation)	2.354	2.857	4.607	0.00355**

This table presents the estimates of the parametric and smooth terms in the GAM model. The parametric term (Intercept) shows the baseline electricity price. The smooth terms include the effective degrees of freedom (edf), reference degrees of freedom (Ref. df), F-statistic, and *P* value for each predictor variable: Deaths, Battles, Wind, Solar Radiation, and Precipitation. Significance levels are indicated by asterisks, with *** denoting $P<0.001$,** denoting $P<0.01$, and * denoting $P<0.05$

The significance of some smoothing terms indicates that the selected variables have a notable effect on electricity prices. In particular, battles, solar radiation, and precipitation are significant factors. The marginal significance of deaths suggests a less pronounced effect, while wind speed does not show a significant impact. Battles significantly affect electricity prices, probably due to infrastructure disruption and associated additional costs. Solar radiation significantly influences prices, possibly due to its impact on solar energy generation. Likewise, precipitation significantly affects prices, probably due to its impact on hydroelectric generation and electricity demand.

In Figure 3, the effects of the variables Battles, Deaths, Wind, Solar Radiation, and Precipitation on the electricity price in Colombia are presented using a GAM model. Each panel presents

Figure 3: Effects of conflict and climate variables on electricity prices using GAM



This figure shows the smoothing curves for the predictor variables: Battles, Deaths, Precipitation, Solar Radiation, and Wind Speed on the electricity prices in Colombia. Each panel displays the relationship between a specific variable and electricity prices, with shaded areas representing the confidence intervals. The y-axis indicates the fitted values, while the x-axis shows the range of each predictor variable. The curves illustrate how changes in each predictor variable affect electricity prices, capturing both linear and non-linear effects

a smoothing curve for a specific variable along with a shaded confidence interval.

The battles curve shows an almost linear increase in electricity prices as the number of battles increases. The confidence interval widens with a greater number of battles, indicating greater uncertainty in the estimates for high values. In Colombia, battles can cause significant damage to electrical infrastructure, increasing repair and maintenance costs. Additionally, conflicts can disrupt the normal operation of power plants, limiting supply and increasing prices. The growing uncertainty may reflect variations in the intensity and location of the battles, which differently impact the electrical infrastructure.

Regarding deaths, the curve shows a decreasing trend in electricity prices as the number of deaths increases, although the slope is gentle and the confidence interval is wide. Although this may seem counterintuitive, this result could be related to the decrease in electricity demand in areas affected by intense conflicts. A higher number of deaths may lead to massive population displacements, reducing local electricity demand and, consequently, prices. However, the relationship is weak and subject to high uncertainty.

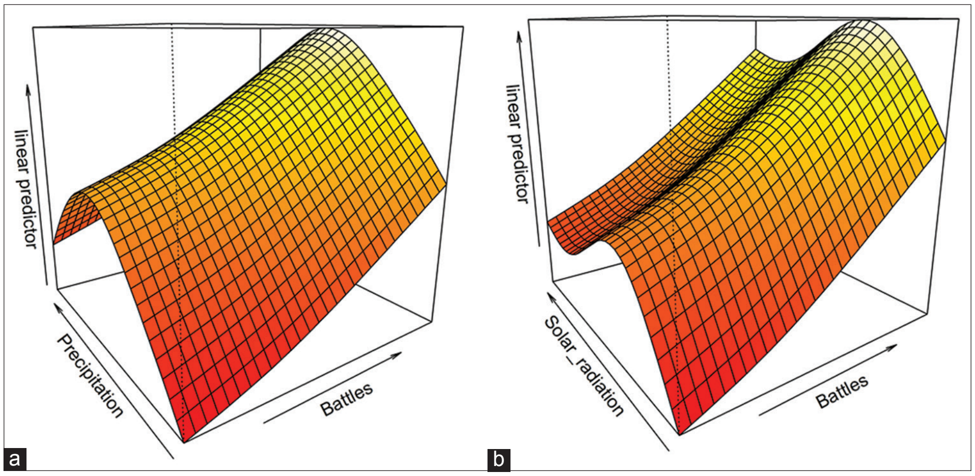
Precipitation, as shown in the next panel, initially causes an increase in electricity prices with increments in precipitation, reaching a peak before decreasing again. The confidence interval widens at the extremes. Precipitation can influence electricity prices in various ways. In Colombia, hydroelectric generation is an important source of electricity. An increase in precipitation can initially improve hydroelectric generation, reducing prices. However, excessive precipitation can cause flooding and damage to infrastructure, increasing costs. The variability in the response reflects these dual effects.

On the other hand, solar radiation presents a non-linear relationship with electricity prices. As solar radiation increases, electricity prices initially decrease but then increase again. Solar radiation affects solar energy generation. Initially, an increase in radiation improves solar energy production, reducing electricity prices due to greater supply. However, extremely high radiation can be associated with adverse weather conditions (such as droughts), which negatively affect other generation sources (such as hydroelectric) and increase prices. This complex effect results in the observed curve.

Finally, wind speed shows little variation in electricity prices with changes in wind speed, and the confidence interval is wide. Wind generation does not seem to have a significant impact on electricity prices in Colombia. This may be because wind energy is not a primary source in the country's energy mix. The wide uncertainty may indicate that although wind contributes to generation, its impact is not large enough to detectably influence prices.

Figure 4, Panel A, shows a 3D surface representing the joint relationship between the number of battles (X-axis), precipitation (Y-axis), and electricity prices (Z-axis, labeled as "linear predictor"). The surface is colored using a color scale ranging from red (lower values) to yellow (higher values), indicating different levels of electricity prices. The 3D surface reveals how the combination of battles and precipitation influences electricity prices. The relationship is not simply additive but shows complex

Figure 4: 3D surface plots showing the joint effects of conflict and climate variables on electricity prices.
Panel A (a) shows the displays the 3D surface plot representing the joint relationship between the number of battles, precipitation, and electricity prices, with the z-axis labeled as "linear predictor." Panel B (b) 3D surface plot representing the joint relationship between the number of battles, solar radiation, and electricity prices. The color scale ranges from red (lower values) to yellow (higher values), indicating different levels of electricity prices. These plots reveal the complex, non-additive interactions between conflict and climate variables and their combined influence on electricity prices in Colombia



interactions between the two predictor variables. Panel B shows the joint relationship between the number of battles and solar radiation.

It is important to clarify that, although we know that climatic and conflict variables are independent and do not directly interact with each other, our goal is to observe how these factors, when considered together, act as determinants of electricity prices. This perspective allows us to better understand how the combination of climatic conditions and conflict events can influence the variability and stability of electricity prices in Colombia. By integrating these variables into our analysis, we seek to capture the complexity of the factors affecting electricity prices, beyond their individual effects.

In regions close to the origin, electricity prices are relatively low, likely due to the stability in infrastructure and energy generation conditions when precipitation is low and battles are minimal. As precipitation increases, electricity prices also tend to rise, modulated by the number of battles. Initially, an increase in precipitation can improve hydroelectric generation, but excessive precipitation can cause flooding and damage, increasing electricity costs. An increase in the number of battles significantly raises electricity prices, especially when the battles are intense. This is due to the disruption of electrical infrastructure and the associated costs of conflicts. The interaction shows that the combined effect of high precipitation and high battle intensity can lead to a pronounced increase in electricity prices. This interaction is relevant because the damage to infrastructure caused by conflicts can be exacerbated by adverse weather conditions, leading to additional costs and a less reliable electricity supply.

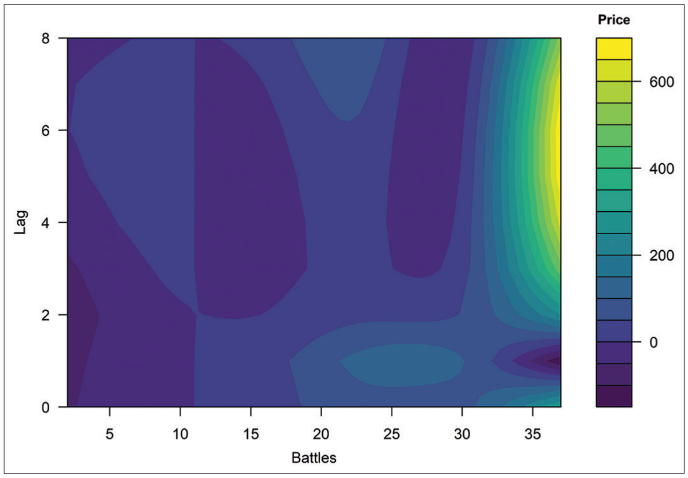
The joint relationship between battles and precipitation is crucial in the Colombian context for several reasons. Colombia relies heavily on hydroelectric generation. Precipitation is a critical factor for energy generation, and its variability can have significant effects on the electricity supply. Armed conflicts in Colombia have historically affected the country's infrastructure, including the electrical infrastructure. Battles can damage transmission lines and power plants, increasing repair and maintenance costs, and reducing supply capacity. Extreme weather conditions, such as heavy precipitation, can cause natural disasters that negatively affect electrical infrastructure. In combination with armed conflicts, these events can exacerbate supply problems and raise electricity prices. Understanding this relationship helps in planning and creating resilience strategies. Policies can focus on strengthening electrical infrastructure against conflict damage and improving disaster response capabilities.

Similarly, the interaction shows that the combined effect of high solar radiation and high battle intensity can lead to a pronounced increase in electricity prices. This interaction is relevant because conflicts can damage solar generation infrastructure, while extreme weather conditions can exacerbate these damages and complicate repairs. Colombia is increasing its solar energy generation capacity. Solar radiation is a critical factor for energy generation, and its variability can have significant effects on the electricity supply. Understanding how solar radiation interacts with other factors is vital for energy planning. Extreme weather conditions, such as high levels of solar radiation that could be related to droughts, negatively affect hydroelectric generation, a major source of electricity in Colombia. These conditions, combined with conflict damage, can lead to a less reliable electricity supply and higher prices.

4.2.2. Temporal effects of conflict on electricity prices

After analyzing the relationship between electricity prices and various variables such as battles, deaths, solar radiation, precipitation, and wind using a GAM model, it was identified that battles have a significant and positive effect on electricity prices in the contemporary lag (week 0). To better understand the temporal dynamics and capture the delayed effects of battles on electricity prices, a DLNM model was employed. This model allows for the evaluation of how the effects of battles propagate over time, from

Figure 5: Contour plot of the temporal effects of battles on electricity prices



This contour plot shows the relationship between the number of battles (x-axis), time lags in weeks (y-axis), and electricity prices (color scale). The color scale ranges from purple (lower prices) to yellow (higher prices). The plot highlights how battles impact electricity prices over time, with significant price increases at higher battle counts and longer lags

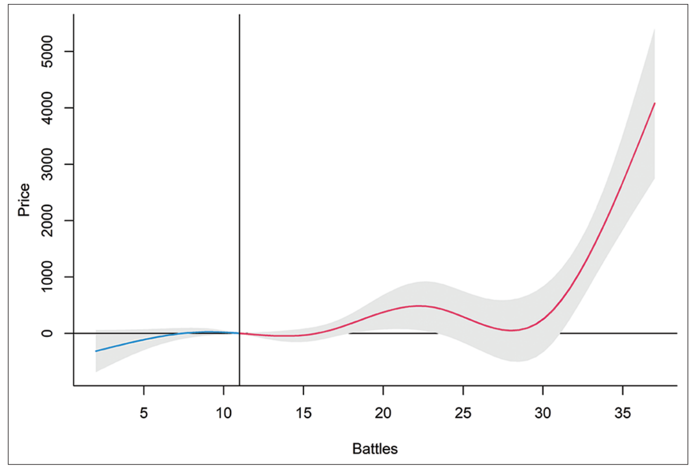
the moment they occur up to 8 weeks later. The following figure shows the results of this analysis, providing a detailed view of how battles influence electricity prices across different temporal lags.

The presented figure 5 is a contour plot showing the relationship between the number of battles (X-axis), the lags in weeks (Y-axis), and the electricity price represented by a color scale. The color scale ranges from purple (lower values) to yellow (higher values), indicating the level of electricity prices. The area near the Y-axis at Lag 0 shows an immediate effect of battles on electricity prices. As observed, a higher number of battles is associated with a significant increase in electricity prices, reflected by the yellow colors in this region. This confirms the results of the GAM model, where battles had a significant impact on contemporary prices. In the 1st weeks after the battles (1-3 weeks), electricity prices show variability, but there is no clear trend towards a significant increase. The colors in this region are predominantly purple and blue, indicating relatively low prices.

As we move to medium lags (4-6 weeks), a zone of high prices is observed when the number of battles is high (more than 30 battles). This area of green and yellow suggests that the effects of battles on electricity prices can reemerge after a certain period. In the longer lags (7-8 weeks), there is a clear trend towards a significant increase in electricity prices when the number of battles is high. The colors in this region change to yellow tones, indicating high prices. This may be due to the cumulative and delayed effects of battles on infrastructure and electricity supply.

It is notable that the impact on electricity prices is more pronounced when the number of battles is considerably high (more than 30 battles). This suggests that not only the occurrence of battles but also their intensity plays a crucial role in determining electricity prices.

Figure 6: Cumulative effect of battles on electricity prices



This plot shows the cumulative effect of battles on electricity prices (y-axis) across different numbers of battles (x-axis). The blue and red lines represent the estimated cumulative impact, with the shaded area indicating the confidence interval. The vertical line at 11 battles marks the median, highlighting the difference in price effects between lower and higher frequencies of battles

Figure 6 shows the cumulative effect of battles on electricity prices across all the lags considered in the DLNM analysis. The vertical line at 11 represents the median number of battles. The effects are visualized with a color line that changes according to the position relative to the median: blue to the left (lower percentiles) and red to the right (higher percentiles). The shaded area around the line indicates the confidence interval, showing the uncertainty of the estimates.

In the left region of the vertical line (0-11 battles), the line is blue. Here, it is observed that the cumulative effect of battles on electricity prices is relatively low and stable. This behavior suggests that, in contexts with a low number of battles, the impact on electricity prices is not significant or is manageable within the normal variability margins of the electrical system.

In the right region of the vertical line (more than 11 battles), the line is red and shows a sharp increase in electricity prices. The cumulative effect of battles on electricity prices increases significantly when the number of battles is higher. This increase suggests that when battles are frequent and intense, the electrical infrastructure is severely affected, considerably raising the costs of electricity generation and supply.

It is notable that uncertainty increases with the number of battles, especially at the far right of the graph. This may be because high-intensity events (more battles) are less frequent, and their effects are more difficult to predict accurately. As the number of battles increases and exceeds the median, not only do electricity prices rise, but also the uncertainty around this estimate, indicating greater variability in the possible outcomes.

This quantile analysis allows us to observe how different levels of battle intensity affect electricity prices. The median acts as a reference point to understand that the most significant and disruptive effects occur in the upper percentile of the battle distribution. Figure 6 highlights the importance of preparing for high-intensity conflict scenarios, as these have a disproportionately high impact on electricity prices. Planning strategies should consider specific mitigation measures for scenarios with a high frequency of battles. The increase in electricity prices in response to a higher number of battles may reflect the rise in operating costs due to infrastructure damage, higher maintenance and repair costs, and the need to implement additional security measures.

5. CONCLUSION

This study has investigated the complex relationship between armed conflicts and electricity prices in Colombia, also considering the effects of climatic variables. Using an empirical approach that integrates Generalized Additive Model (GAM) and Distributed Lag Non-linear Model (DLNM), significant conclusions have been drawn about how these variables interact and affect electricity prices.

Firstly, the results obtained through the GAM model revealed that battles, solar radiation, and precipitation are significant factors influencing electricity prices. Battles showed an immediate positive effect, increasing contemporary electricity prices. This finding underscores the vulnerability of the Colombian electrical system to armed conflicts, where critical infrastructure can be damaged, generating additional repair and maintenance costs that are reflected in electricity prices.

The DLNM analysis allowed for a deeper understanding of the temporal and delayed effects of battles on electricity prices. It was observed that, although the immediate impact of battles is significant, the effects can reemerge after a certain period, particularly between weeks 4 and 6, and again in weeks 7 and 8. This behavior suggests that cumulative damage and prolonged disruptions to electrical infrastructure can have long-term repercussions on electricity costs. Additionally, it was highlighted that the intensity of battles, not just their occurrence, is a crucial determinant of price increases.

The integration of climatic variables into the analysis showed that both solar radiation and precipitation have non-linear effects on electricity prices. Solar radiation initially decreases prices due to increased solar energy generation, but extreme increases can be associated with adverse weather conditions, such as droughts, which negatively affect other generation sources like hydroelectric. Similarly, precipitation has a dual effect: While a moderate increase improves hydroelectric generation and reduces prices, excessive precipitation can cause damage and flooding that increase costs. The contour plots and 3D surfaces used to visualize the DLNM results revealed the complex interaction between battles and climatic variables. These graphs showed how the combination of high precipitation and high battle intensity can lead to significant increases in electricity prices, highlighting the need to consider these factors jointly in the planning and management of the electrical system.

The findings of this study emphasize the importance of addressing both socio-political and climatic factors in the management and planning of the electrical sector in Colombia. Resilience strategies should include measures to mitigate the impacts of armed conflicts, improve infrastructure to withstand damage, and adapt to climatic variations. A detailed understanding of how these factors interact provides a solid basis for the formulation of public policies and operational strategies that ensure a more stable and sustainable electricity supply in the country. This study contributes to the existing literature by offering a comprehensive and long-term empirical analysis, highlighting the interdependence between conflicts and climatic conditions in determining electricity prices.

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