A METHODOLOGICAL APPROACH FOR CLIMATE CHANGE RISK ASSESSMENT IN THE POWER SECTOR: A CASE STUDY IN COLOMBIA

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Eduardo José Sánchez-Sierra, Diego Grajales, Oscar Galvis

Ministry of Mines and Energy, Colombia

NREL Technical Monitor: Sadie Cox

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List of Acronyms

ENSO	El Niño-Southern Oscillation
GDP	gross domestic product
IPCC	Intergovernmental Panel on Climate Change
MME	Ministry of Mines and Energy

Executive Summary

This case study presents the climate change risk assessment methodology developed by the Colombia Ministry of Mines and Energy and the results of a pilot assessment for the power sector in Colombia. This methodology incorporates climate change scenario uncertainties and strengthens links between meteorological/climate data, risk assessment results, and experts' feedback. The methodology also allows stakeholders to identify the threats and risks that are relevant for power generation and transmission technologies, considering location, possible occurrence of climate events, and the territory's vulnerability. The Colombia Ministry of Mines and Energy applied the methodology to understand the possible climate change impacts on the power system; the results will help inform potential adaptation strategies for the design, planning, and operation of the power sector.

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1 Context

Power sectors worldwide face myriad natural, technological, and manmade threats that can disrupt the provision of reliable, secure, and affordable electricity. Nonetheless, policymakers, planners, and system operators can systematically plan for and mitigate threats by enhancing power sector resilience. This case study highlights how representatives from the Colombian Ministry of Mines and Energy (MME) assessed climate change risks to Colombia's power sector.

Damage and costs wrought by climate change are likely to be significant and scalable over time (IPCC 2014) which calls for a robust understanding of climate change impacts on, and capacities of, different sectors of the economy, including the power sector. Adapting to these changes is a dynamic, evolving process marked by the inherent uncertainty in climate change projections. Climate risk assessment methodologies are a useful tool for power sector resilience planning in the face of uncertainty.

This case study presents the climate change risk assessment methodology developed by the MME and the results of a pilot assessment for the power sector in Colombia. This methodology incorporates climate change scenario uncertainties and strengthens links between meteorological/climate data, risk assessment results, and experts' feedback. The methodology also allows stakeholders to identify the threats and risks that are relevant for power generation and transmission technologies, considering location, possible occurrence of climate events, and the territory's vulnerability. The MME applied the methodology to understand the possible climate change impacts on the power system; the results will help inform potential adaptation strategies for the design, planning, and operation of the power sector.

1.1 Diagnosis of the Power Sector

Colombia has an electricity mix of 70% hydro with thermal backup (XM n.d.) and overall reliability of 96.53% (UPME 2019). Due to significant water requirements, the risk posed by water scarcity to Colombia's hydro-dependent power sector demands deeper knowledge of the interactions between climate and power generation. Due to its dependency on hydropower, Colombia's power sector operations fluctuate with changes in climatic variables. For example, Figure 1 exemplifies hydro and thermal outputs over the last 10 years, showing operational changes during dry periods. During 2009-2010 and 2015-2016, the weather phenomenon El Niño led to spikes in thermal generation, close to 50% of the total generated power (XM 2016), not only increasing CO_2 emissions but also stressing the power system (XM 2016).

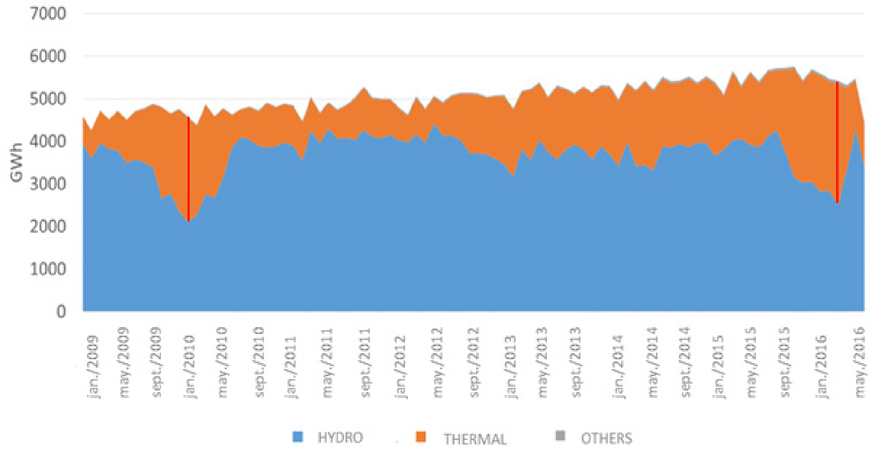


Figure 1. Historical power generation during a dry period in Colombia

Source: Adapted from (XM s.f.)

The El Niño-Southern Oscillation (ENSO) episodes (i.e., El Niño/La Niña) also influence electricity consumption in Colombia. Figure 2 shows a correlation between electricity consumption and gross domestic product (GDP), population, and temperature. During El Niño, electricity consumption increases, likely because of high temperatures that drive increased cooling demand.

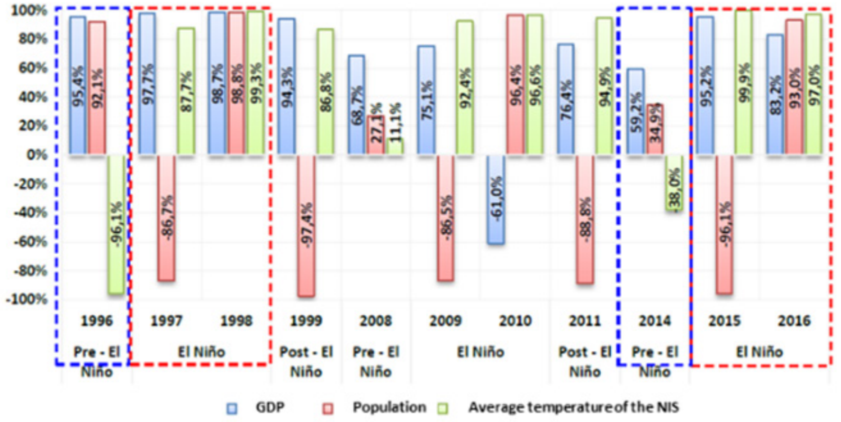


Figure 2. Historical correlation of electricity consumption with GDP, population, and average temperature

Source: (UPME 2018)

These variations in generation and consumption show how dependent the power sector in Colombia is to climate dynamics; in addition, they highlight the need to determine how that dependency could increase due to climate change impacts and climate variability, such as variations of precipitation and/or temperature, water scarcity, floods, landslides, forest fires, heatwaves, sea level rise, windstorms, and/or hurricanes.

2 Risk Assessment Methodology

The climate change risk methodology aims to: (i) understand the climate change hazards to which the power system is exposed; (ii) assess power system vulnerability; and (iii) provide guidelines for decision makers to enhance the competitiveness of the power sector in Colombia. This section explores the general scope for the methodology's development and the risk assessment methodology defined and adopted by the MME.

2.1 Development of the Risk Assessment Methodology

A risk assessment is a process used to evaluate the risk level associated with any type of hazard, in this case those related to climate change and climate variability. MME originally developed a risk assessment methodology fitted to Colombian conditions (territory and the variations of its climate patterns) that could be extrapolated to other scales (sectors, countries, regions, or towns). Over time, the methodology has been updated to scrutinize climate change hazards that historically have had the most harmful effects on the mines and energy sectors. The methodology's scope has since expanded to include climate change scenarios and an analysis of climate variability.

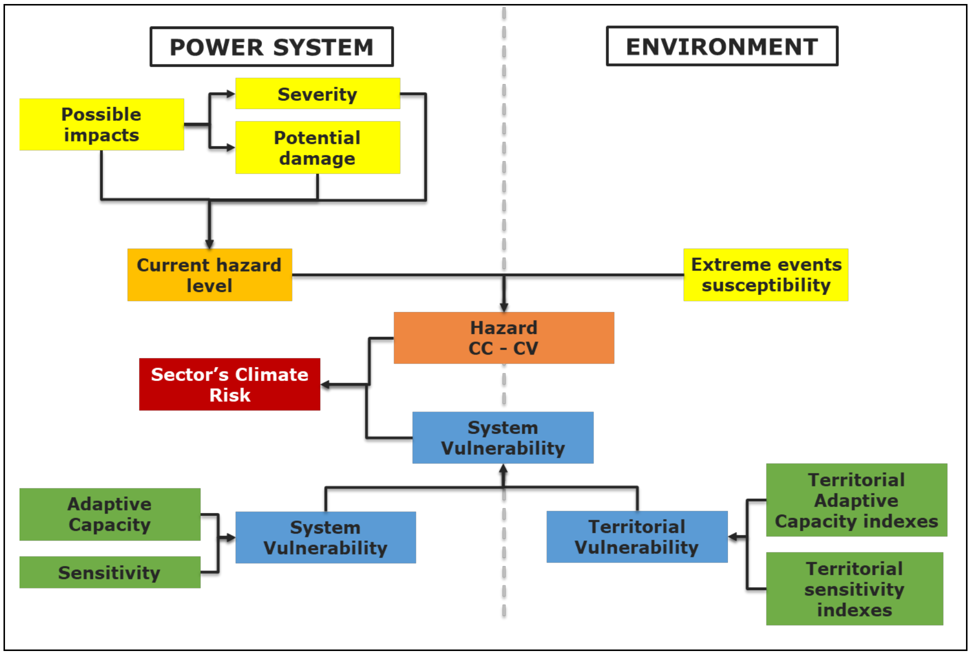


Figure 3. Risk assessment framework

Source: Author (2020)

The methodology's updates guided the MME to consider the structural variables of risk in light of the territory's response to climate change and include the power system operation as part of the vulnerability assessment. Figure 3 shows the methodology's framework. The methodology considers both the operation and the environment where it is located, analyzing both climate change and climate variability; it follows a process where hazards affect the system's vulnerability resulting in increased risks.

2.1.1 Risks to Be Addressed: Operational Risk Versus Structural Risk

The energy sector depends greatly on infrastructure. A conventional risk assessment of infrastructure does not consider the interaction between those risks and those of the broader environment. To increase the sector's resilience, the impact of a possible climatic event should be assessed by both considering the sector's operations at a local scale (region where the operations are located), and how the sector's operating conditions may or may not exacerbate climate impacts on the broader environment. This difference between the operative (i.e., company-scale) and structural (i.e., broader environment) risk is the keystone of this risk assessment methodology because it assesses the structural risk instead of the operative risk.

For example, an increase in upstream discharge could generate direct impacts on the infrastructure of a hydroelectric plant. The plant design must consider some critical conditions to ensure the capacity to withstand potentially high levels of water discharge. If the climatic patterns of the region change until the point where the average water discharge reaches or surpasses the critical design value, the infrastructure could malfunction or, ultimately, fail. In this case, the hydroelectric plant must implement strategies to increase its capacity and safely operate under the new conditions. These strategies or measures will enhance the real operation of the system (at the local scale) and reduce risks under the new climatic conditions. In other words, the strategies will reduce operational risks.

On the other hand, the presence of infrastructure itself could exacerbate the impacts that climatic change could generate on the territory, for example fires caused by grid networks on forested areas. Infrastructure can generate new impacts (known as indirect impacts) on the territory by disrupting the natural dynamics of ecosystems; over the long term, those disruptions could exacerbate the operational risk in the future; therefore, a risk assessment should evaluate not only operational risks but also possible impacts on the broader environment, known as structural risk. One way to address both operational and structural risk is to focus on identifying and enhancing ecosystem services.

2.1.2 Structural Elements of Risk

The interplay between vulnerability, exposure, and hazards shape the degree of risk. Vulnerability represents a propensity or predisposition to being adversely affected (IPCC 2012); it is a combination of sensitivity, which seeks to qualify the strength of the system to face external shocks, and adaptive capacity, which is the ability to recover from a damage caused by a climate event. Exposure is the presence of system assets in places that could be adversely affected. A hazard is the possibility that a climate event negatively impacts a system.

The Intergovernmental Panel on Climate Change (IPCC) framework to understand the interaction between hazards, vulnerability and exposure on risk is divided into two parts: (i) Socio-economic development, which influences vulnerability and exposure; and (ii) Climate, which directly relates to hazards as is shown in Figure 4.

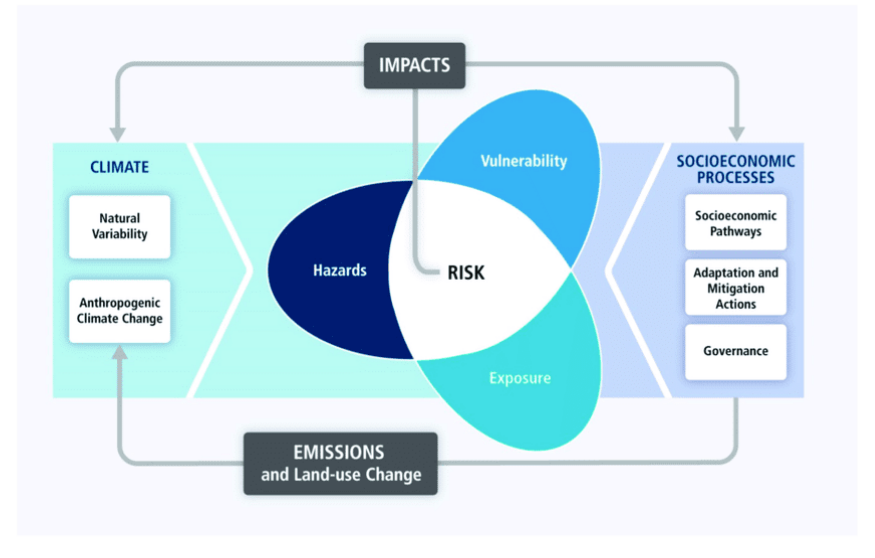


Figure 4. Structural risk variables interaction

Source: IPCC 2012

The previous example of the hydroelectric plant is useful for understanding this framework. In the region where the plant is located, there could be interactions between the three risk variables. For instance, a lack of strict design variables could affect the plant's vulnerability; its location determines its exposure, while the possible occurrence of a climatic event—a hazard—could arise due to the climatic and geographical conditions in the region. As the climatic patterns change over time, the design and operation of the plant will determine if the new climatic conditions negatively impact the system. To assess risk, the methodology evaluates the interactions between the conditions of a climatic event (hazard) and the system's operation (vulnerability) on a specific region (exposure). The result of those interactions is risk measured by the possibility of an operative risk occurring. Adaptation strategies must modify either system vulnerabilities and/or modify exposure which will reduce the interaction area between risk variables (see Figure 5).

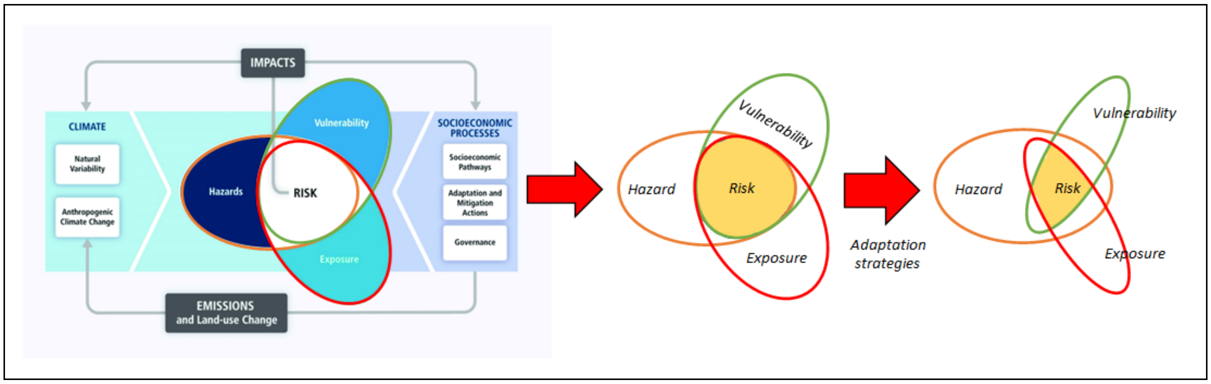


Figure 5. Different risk scenario based on changes to vulnerability and exposure

Source: Adapted from IPCC 2012

When a risk materializes in a region, it generates an impact. A risk assessment methodology analyzes two kinds of impacts: direct and indirect. Direct impacts are the effects on energy operations due to climatic events, while the indirect impacts are those that affect energy operations within the context of the broader environment where the infrastructure is located and the electricity market it supplies. The methodology does not analyze these kinds of impacts separately; instead, it analyzes their interaction. Figure 6 illustrates the interaction of direct and indirect impacts of a climatic event on the power system and the broader environment.

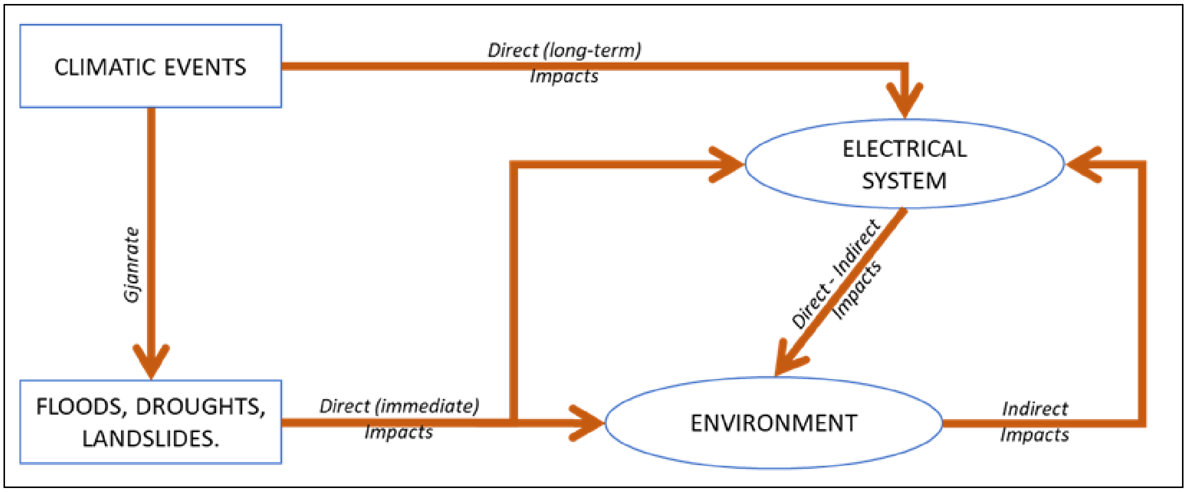


Figure 6. Typology of risk impacts on the power system

Source: Author (2020)

2.2 MME Risk Assessment Methodology

The IPCC risk assessment methodology provides insights on the way hazards, exposure, and vulnerability work within a system, however there are multiple ways to understand risk. The approach that Colombia's MME took was based on one key objective: avoid shortfalls of production and distribution of energy products, assuming exposure as a constant and focusing on hazard and vulnerability as key drivers to be analyzed.

2.2.1 Hazards

To analyze the hazards to which the system is exposed, the MME developed a potential hazards matrix. This matrix takes into consideration the hazards' severity, which is the product of an event's damage potential and the possibility of occurrence in the given region. The damage potential is an estimation of the severity of the overall impact on the system by each component; it considers the relevance of the affected elements on the system's operation and an estimate of the severity of the operation's disruption. The occurrence possibility is determined by the probability of a certain event based on historical information. Table 1 illustrates how the damage potential combined with the possibility of occurrence results in the hazard's severity.

Table 1. Hazard Severity Values

HAZARD'S SEVERITY		**OCCURRENCE POSSIBILITY**		
		UNLIKELY	**POSSIBLE**	**CERTAINLY POSSIBLE**
POTENTIAL DAMAGE	**VERY LOW**	VERY LOW	VERY LOW	LOW
	LOW	VERY LOW	LOW	MEDIUM
	MEDIUM	LOW	MEDIUM	HIGH
	HIGH	MEDIUM	HIGH	VERY HIGH
	VERY HIGH	HIGH	VERY HIGH	VERY HIGH

Source: (INERCO, and UNAL 2017)

To analyze the hazards related to the system's environment, the analysis considers the virtual possibility of occurrence of the event in a region, otherwise known as susceptibility of occurrence. The location of all power system components (i.e., infrastructure) was mapped and then overlaid with the virtual susceptibility maps of relevant events.

At this point, the assessment presents an understanding (i.e., an actual scenario) of the response of energy sector components that are exposed to the recurrent climatic hazards on the region. To expand the assessment to the projected behavior of the climate hazards, climate change, and climate variability scenarios must be included. In the Colombian case, the Third National Communication of Climate Change (IDEAM 2015) presents precipitation and temperature future scenarios expected between 2011-2040 for Colombia. As part of these national guidelines, Colombia has analyzed the effect of ENSO on the climatic patterns, which provides the inputs for climate variability information. In that way, the assessment already includes projected scenarios of climate change and climate variability (ENSO episodes). The cartographic overlap between the actual scenario and the projected scenarios, results in a map of the prospective hazard scenarios of the sector with affected areas by climate change and climate variability.

2.2.2 Vulnerability

MME's risk assessment methodology includes a vulnerability assessment, which has two main components: sensitivity and adaptive capacity.

The sensitivity of the system is related to its structural organization. An analysis of sensitivity is divided into three general aspects, which have different factors to be evaluated. Each factor is evaluated by indicators, which give a qualitative idea of the tendency of the system to be negatively impacted. The criteria used to define the indicators of sensitivity are shown in Table 2.

Table 2. Sensitivity Criteria

ASPECT	FACTORS
Corporate Structure	Planning, management, and performance efficiency
	Operative capacity
	Processes quality
Technical operation	Operation sensibility
Physical infrastructure	Infrastructure quality

Source: (INERCO, and UNAL 2017)

On the other hand, adaptive capacity is related to the availability of resources to act and react during and after an event. These resources help the system reduce its vulnerability and improve its response time and preparedness. Like the sensitivity analysis, three general aspects are considered with specific factors to be evaluated. The criteria used to define the adaptive capacity indicators are shown in Table 3.

Table 3. Adaptive Capacity Criteria

ASPECTS	FACTORS
Financial resources	Assets
	Liquid assets
Corporative resources	Human Resources
	Corporate commitment
	Collaboration mechanism and diffusion strategies
Institutional resources	Sectorial regulation

Source: (INERCO, and UNAL 2017)

Each indicator has a relative weight in the evaluation. Both analyses are completed by summing the relative weights of their indicators; those values are sorted and grouped by ranges. Finally, a matrix matches both variables (i.e., sensitivity and adaptive capacity) so that a system's vulnerability can be assessed (see Table 4).

Table 4. System Vulnerability Matrix

SYSTEM'S VULNERABILITY		ADAPTIVE CAPACITY				
		VERY LOW	LOW	MEDIUM	HIGH	VERY HIGH
SENSITIVITY	VERY LOW	MEDIUM	MEDIUM	LOW	VERY LOW	VERY LOW
	LOW	HIGH	MEDIUM	LOW	LOW	VERY LOW
	MEDIUM	HIGH	HIGH	MEDIUM	LOW	LOW
	HIGH	VERY HIGH	HIGH	HIGH	MEDIUM	LOW
	VERY HIGH	VERY HIGH	VERY HIGH	HIGH	MEDIUM	MEDIUM

Source: (INERCO, and UNAL 2017)

2.2.3 Risk

After the hazard and vulnerability assessments, the next step is to assess the risk due to a climatic event in the specified region, based on the location of the system's components and the hazard's severity. To do so, a map of the prospective hazards per event and power system components is developed. This approach simplifies the risk assessment so that it focuses only on areas with plausible risk and power system components. The final product is a matrix of prospective risk scenarios per event and power system component.

3 Study Case: Risk Assessment for the Power Sector in Colombia

After the development of the methodology, the MME applied a climate risk assessment to the power sector in Colombia as a case study. The objective of the assessment was to foster policies that would enhance the power sector's competitiveness by reducing climate change risks. Climate change impacts on the power sector are the result of the interplay between the system's environment, socio-economic structures, and climate events. The likelihood of those impacts is related interactions between ecosystems and socio-economic structures. The results of this risk assessment shed light on the physical stresses of the power system, possible future causes of regional conflicts (e.g., water use conflicts), and the sector's sustainability.

The risk assessment followed two approaches (based on the methodology in Section 2.2). The first approach took the effect of mean climatic path changes (climate change scenarios) into consideration; the second one took the effects of exacerbated ENSO episodes (climate variability scenarios) into consideration. Both scenarios are shown in Table 5.

Table 5. Differences Between the Analysis Scenarios—Power Sector

	CLIMATE CHANGE SCENARIO	**CLIMATE VARIABILITY SCENARIO**
CLIMATIC DRIVERS	• Temperature • Precipitation	• Temperature • Precipitation • 'El Niño' episode conditions • 'La Niña' episode conditions
ANALYZED SUB-EVENTS	• Water scarcity • Floods • Landslides • Forest fires • Temperature increment • Sea level rise • Storms and Hurricanes	El Niño • Water scarcity • Forest fires • Temperature increment La Niña • Floods • Landslides
SUBCOMPONENTS ANALYZED	• Hydroelectric generation, thermoelectric generation, wind generation, solar generation, and transmission	
REPRESENTATIVE CONCENTRATION PATHWAY - RCP	RCP 6.0* Radiative forcing: 6.0 W/m2 CO_2 eq atmospheric concentration (ppm): 850 Characteristics: • High dependency on the fossil fuels • Intermediate power intensity • Changes of the land use by increasing crops and reduction of grass • Stable methane emissions • The CO_2 emissions reach their maximum level in 2060 (75% higher than the actual levels), and afterwards they are reduced to 25%.	

Determined by analyses of vulnerability and risk analysis of IDEAM

3.1 Risk Assessment Results

To have a general perspective of the climatic risk on the power sector, the analysis were developed component by component and per subevent, the mean result was calculated based on the results per state in the Colombian territory. The results summary gives the compile scenario to consider in the planning processes.

As the first step, before different climatic events were analyzed, the mean prospective hazard related to hydroelectric generation (Figure 7) was calculated based on the analysis framework outlined in Table 1, and applied spatially over a map of Colombia.

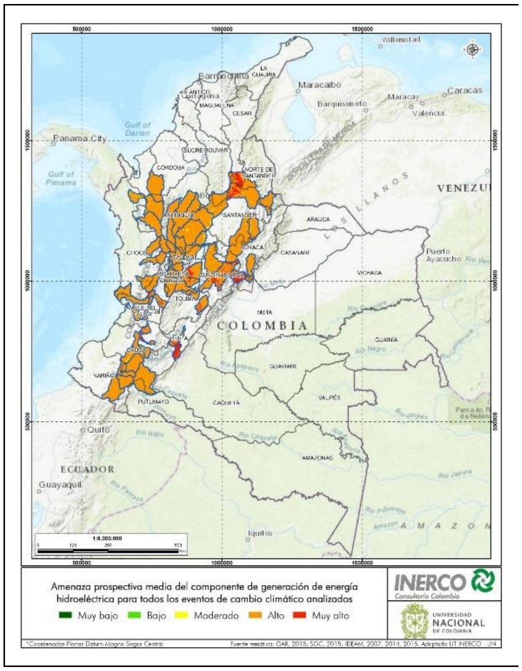


Figure 7. Mean prospective hazard—hydroelectric generation

Source: (MME 2018)

Vulnerability was calculated as well, based on the variables shown in Table 2 and Table 3, producing the results in Table 6.

Table 6. Vulnerability Index of the Power System

ASPECT	GENERATION	TRANSMISSION
Sensitivity	Low	Low
Adaptation capacity	High	High
System’s vulnerability	Low	Low

Source: (MME 2018)

Based on the general aspects evaluated, the general vulnerability index for the power sector in Colombia is low. After the overlap of the hazard and vulnerability analyses, the climate risk was assessed. Figure 8 shows a comparison of the risk variables under a climate change scenario for each hazard assessed, including water scarcity, floods, landslides, forest fires, heat waves, sea level rise, and windstorms. In addition, the Table 7, Table 8, and Table 9 show the risk matrix for each scenario.

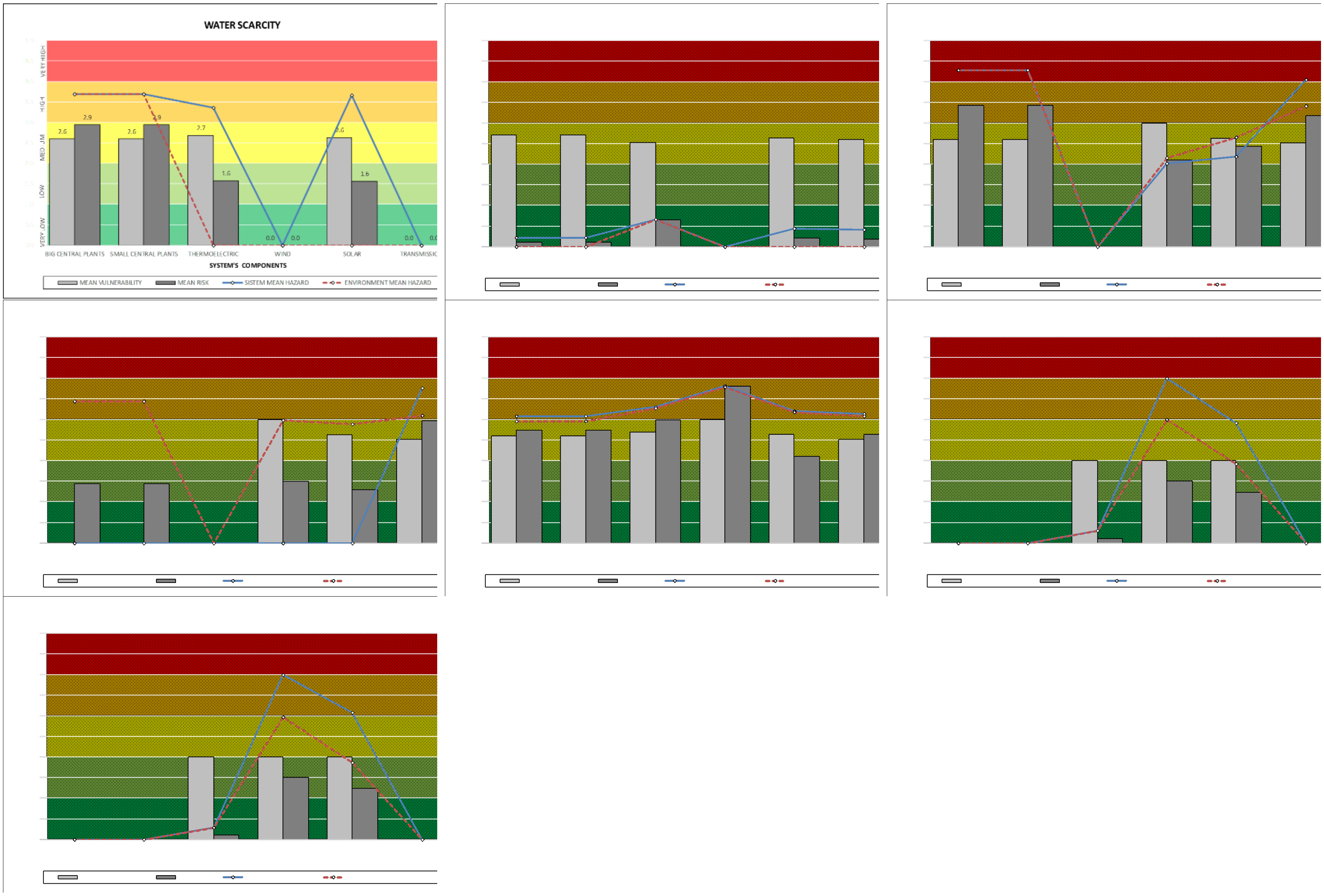


Figure 8. Statistical risk assessment results for all components—Climate Change Scenario

Source: Author (2020)

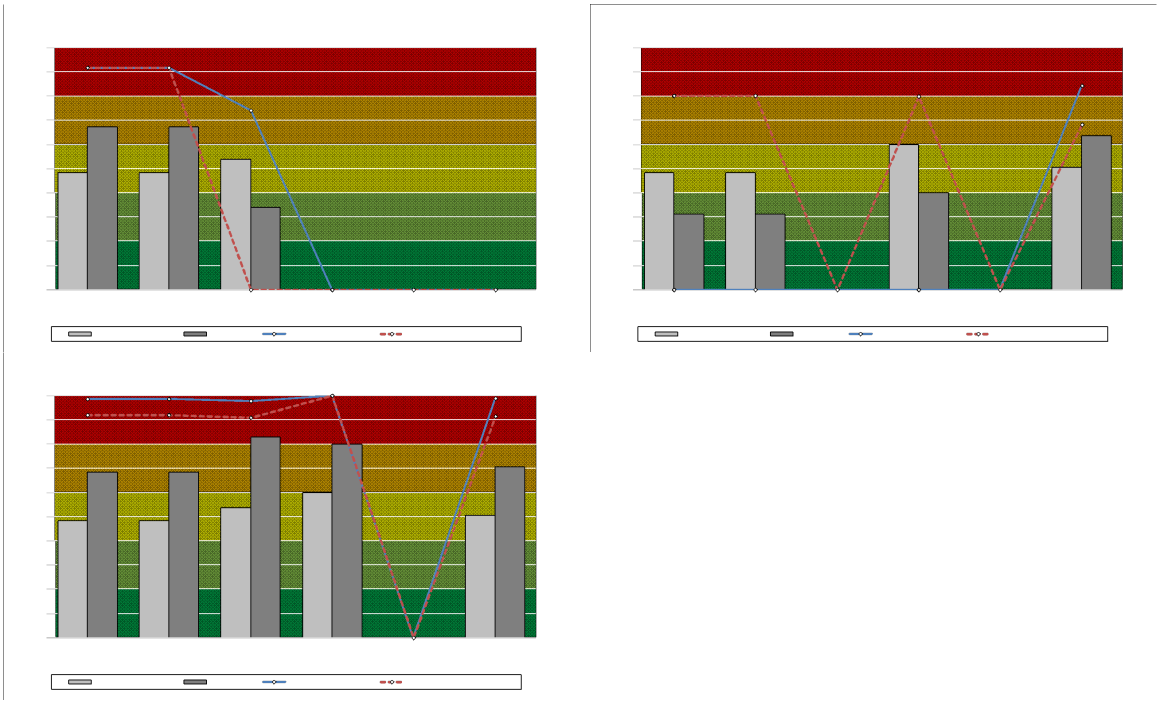


Figure 9. Statistical risk assessment results for all the components—El Niño Scenario

Source: Author (2020)

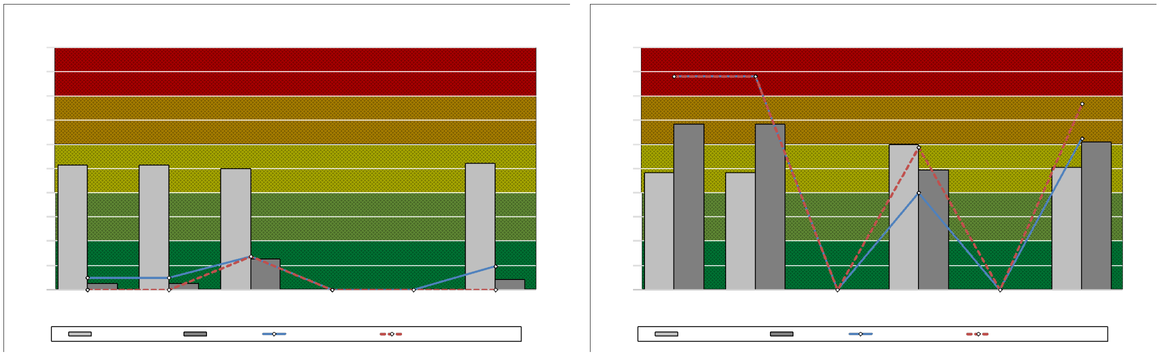
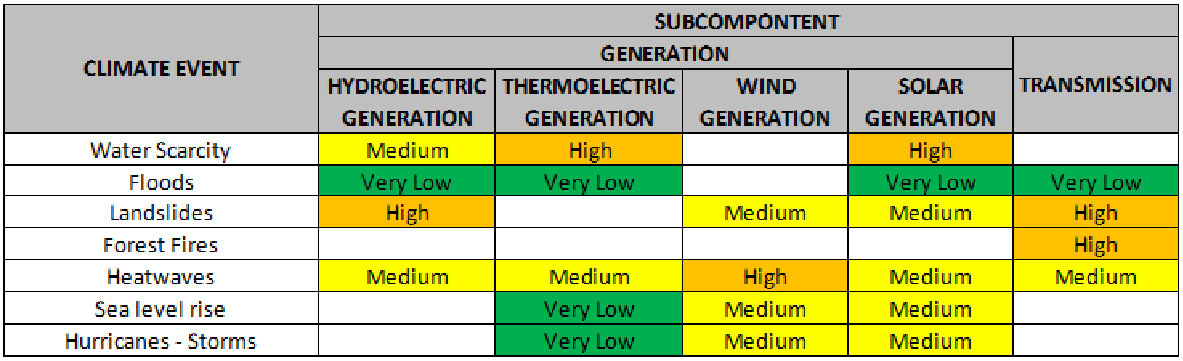


Figure 10. Statistical risk assessment results for all the components—La Niña Scenario

Source: Author (2020)

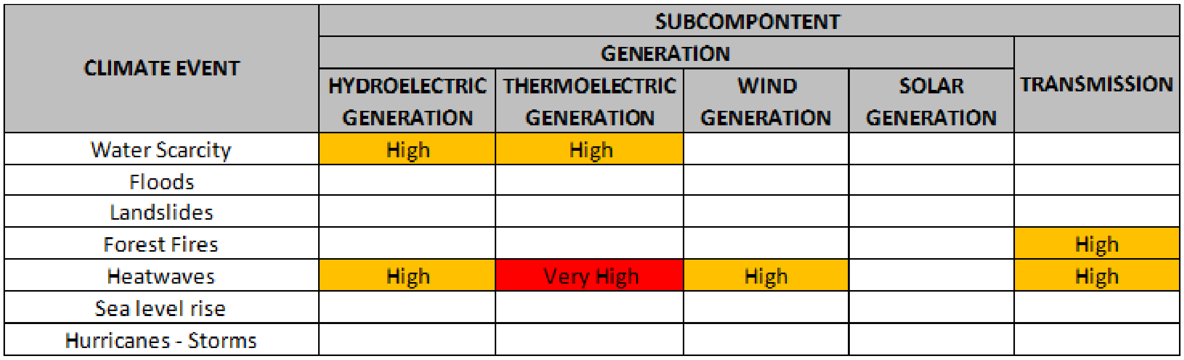
Table 7. Risk matrix for Climate Change Scenario



CLIMATE EVENT	SUBCOMPONTENT				
	GENERATION				TRANSMISSION
	HYDROELECTRIC GENERATION	THERMOELECTRIC GENERATION	WIND GENERATION	SOLAR GENERATION	
Water Scarcity	Medium	High		High	
Floods	Very Low	Very Low		Very Low	Very Low
Landslides	High		Medium	Medium	High
Forest Fires					High
Heatwaves	Medium	Medium	High	Medium	Medium
Sea level rise		Very Low	Medium	Medium	
Hurricanes - Storms		Very Low	Medium	Medium	

Source: Author (2020)

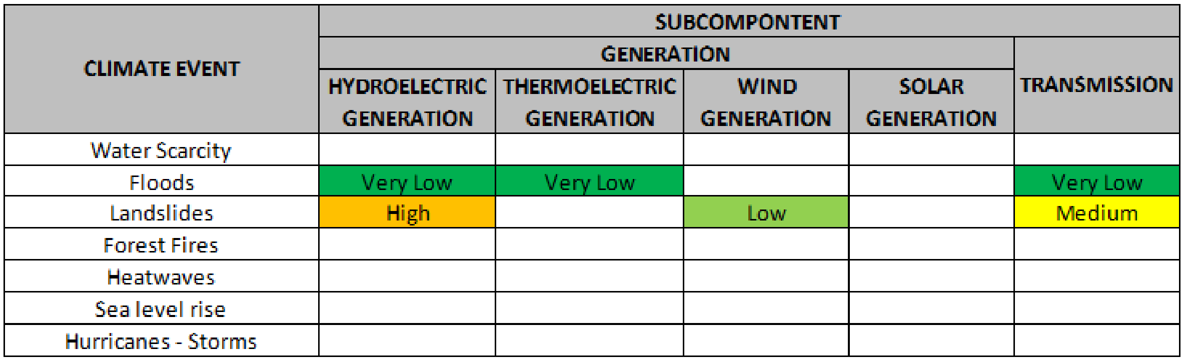
Table 8. Risk matrix for "El Niño" Scenario



CLIMATE EVENT	SUBCOMPONTENT				
	GENERATION				TRANSMISSION
	HYDROELECTRIC GENERATION	THERMOELECTRIC GENERATION	WIND GENERATION	SOLAR GENERATION	
Water Scarcity	High	High			
Floods					
Landslides					
Forest Fires					High
Heatwaves	High	Very High	High		High
Sea level rise					
Hurricanes - Storms					

Source: Author (2020)

Table 9. Risk matrix for "La Niña" Scenario



CLIMATE EVENT	SUBCOMPONTENT				
	GENERATION				TRANSMISSION
	HYDROELECTRIC GENERATION	THERMOELECTRIC GENERATION	WIND GENERATION	SOLAR GENERATION	
Water Scarcity					
Floods	Very Low	Very Low			Very Low
Landslides	High		Low		Medium
Forest Fires					
Heatwaves					
Sea level rise					
Hurricanes - Storms					

Source: Author (2020)

This comparison shows that landslides and heat waves are the biggest risks for the electricity sector in Colombia (Figure 8); however, the power system faces huge vulnerabilities (between medium and high) more broadly, especially during El Niño episodes, where the capacity of the power system (both hydro and thermal generation) is pushed to extremes due to heat waves and water scarcity (Figure 9). This finding reinforces the need to diversify the energy mix to reduce risk and uncertainty. Complementarity of energy resources is of paramount importance as the use of different technologies (e.g., wind, solar thermoelectric, big central plants, small central plants) shown in Figure 8, Figure 9, and Figure 10, can reduce the risks associated with the use of a single technology, and ameliorate the concentrations of particular risks shown in Figure 11 to Figure 15.

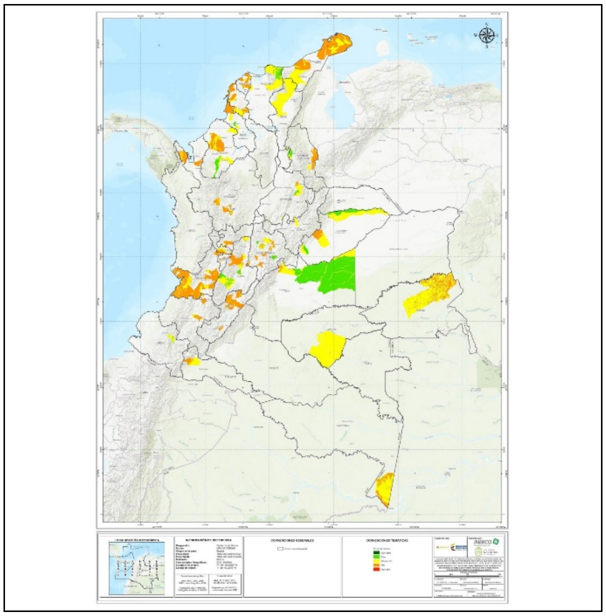


Figure 11. Mean risk solar generation—Climate Change Scenario

Source: (MME 2018)

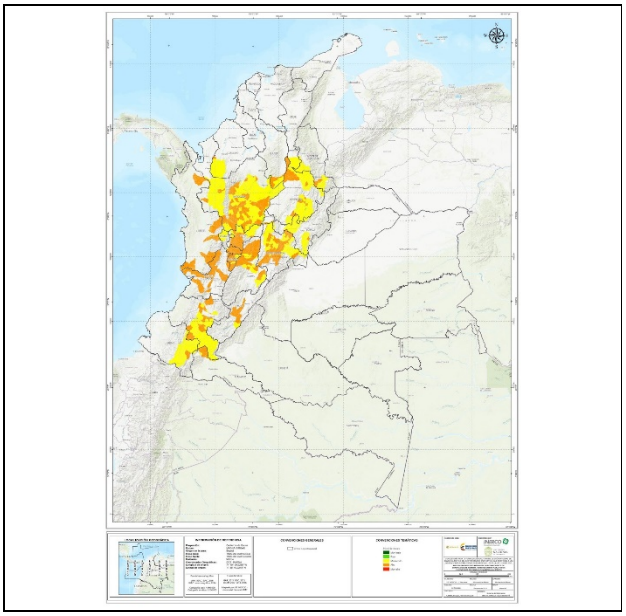


Figure 12. Mean risk hydroelectric generation—Climate Change Scenario

Source: (MME 2018)

Figure 13. Mean risk thermoelectric generation—Climate Change Scenario

Source: (MME 2018)

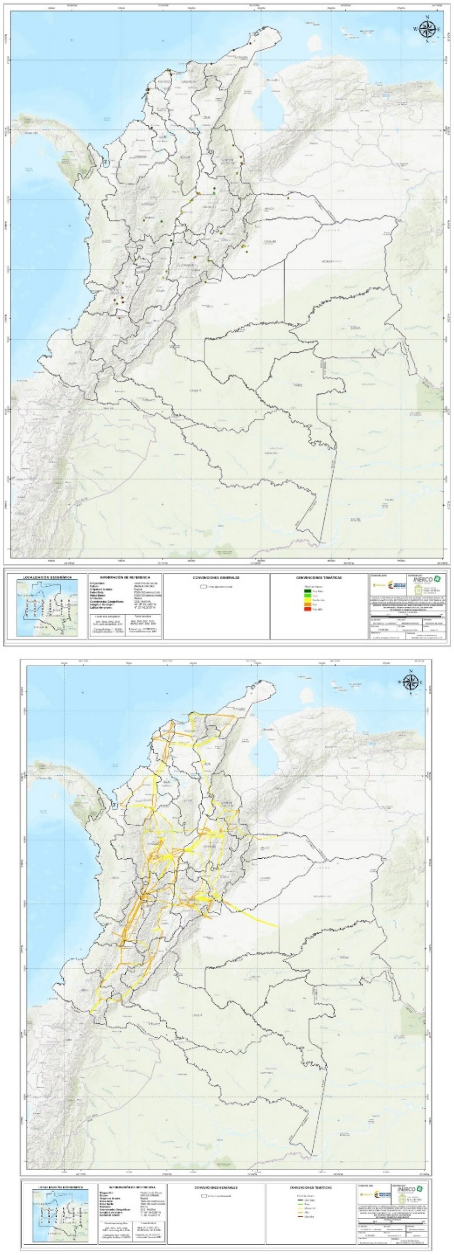


Figure 14. Mean risk transmission—Climate Change Scenario

Source: (MME 2018)

Figure 15. Mean risk wind generation—Climate Change Scenario

Source: (INERCO—Universidad Nacional de Colombia, 2017)

Figure 8 to Figure 15 show the risks embedded in each technology from a geographical perspective, allowing for comparison and analysis of location versus risk. This information can inform policy and action recommendations to enable resilience. As part of these recommendations, Figure 14 shows that the transmission system requires special attention as there is no point in diversifying the energy mix if the grid possesses the risk level currently shown.

Compared with other technologies, wind generation (Figure 15) does not show comparable risk levels due to the fact that it is currently underdeveloped and located in a very specific area of the north of the country with marginal generation; however, as the use of this technology increases, further risk analysis will be required.

4 Conclusions and Uncertainty Management

The results of the methodological approach led to the design of 29 actions that can be found on the Act 40807 of 2018 within four strategic categories:

- Resilient Infrastructure
- Short and Long-Term Planning
- Landscape Management
- Information.

The main objective of these actions was to reduce risk and increase capabilities in terms of information and analytics to improve further risk analysis, given that this process is iterative and can be improved.

In terms of implementation, the results of the methodology are being used by the MME to develop a new early warning system for the energy sector and an adaptation project based on ecosystems protection, which will further test the methodology results and bring data and approaches able to improve it.

The role of ecosystem services is a cornerstone of the methodology because of the dependence of any economic activity on those services. In fact, economic activity and ecosystem services have a two-way relationship, therefore, being able to isolate and quantify the amount of "service" provided and consumed should be a priority in following versions of the methodology.

After almost five years since the first version of the methodology, one thing is clear: uncertainty is always an important factor to consider. The effects of the 2020 coronavirus pandemic, not only on energy demand but also in the dynamics between livelihoods and environment, are a clear example of that. Uncertainty can be managed but not removed. Information can be used to model what is known, but not for modeling the unknown. Therefore, uncertainty management requires both improved information and approaches. In addition, the correlation of projected events with previous ones can be examined in future methodological updates to support modeling results and inform policy decisions.

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Jeremy Foster
U.S. Agency for International Development
Email: jfoster@usaid.gov

Sarah Lawson
U.S. Agency for International Development
Email: slawson@usaid.gov

Sadie Cox
National Renewable Energy Laboratory
Email: sadie.cox@nrel.gov

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