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Powering decisions: A case study of weather and climate services in Senegal's energy sector

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ABSTRACT

Climate services are essential inputs for decision-makers in the energy industry to improve the energy system's resilience to weather and climate variability and change. The impacts of climate change on the energy system have been discussed over the past decades, and appropriate weather and climate services will help minimize the effects by strengthening resilience and adaptive capacity in the energy sector. However, despite the increasing recognition of their importance, weather and climate services tailored to the energy sector remain limited in West Africa. Climate services assessment for the energy sector is scarce in West Africa. This study presents a case study of the current state of weather and climate services for the energy sector in Senegal based on interview results. The information was collected through a face-to-face interview, which allows direct interaction with the experts. A total of seventeen experts participated in the interview, all working in the energy (thermal, solar, wind) and meteorological sectors. The data was analyzed to identify common themes and patterns. The results from this study show a lack of collaboration between institutions. A need for better communication and exchange between the National Meteorological Office and the energy sector was identified. It also emerged from the interview that most of the participants from the energy sector are willing to receive tailored weather and climate services from the National Meteorological Office. This information is useful for decision-makers to address gaps and improve the energy sector's resilience.

Practical implications

The study highlights the critical role that weather and climate services can play in supporting the resilience and sustainability of Senegal's energy sector. The findings indicate that while institutional frameworks such as the Global Framework for Climate Services (GFCS) and the National Framework for Climate Services (NFCS) provide a foundation for climate-informed decision-making, the energy sector remains underrepresented compared to agriculture, fisheries, and health. Strengthening weather and climate services for the energy sector requires bridging institutional gaps, improving data accessibility, building and strengthening collaborations, and tailoring information products to the specific needs of the energy stakeholders.

- **Enhancing Decision Making and Operational Efficiency**

Integrating climate information into energy planning and operations offers benefits for both renewable and conventional energy sources. Variations in climate parameters such as temperature, wind speed and direction, solar radiation, humidity, and precipitation significantly affect energy production and use. Operators reported that extreme wind events can trigger automatic shutdowns of turbines, and high temperatures can reduce photovoltaic efficiency. Incorporating timely forecasts into maintenance schedules, for instance, planning panel cleaning around anticipated sandstorms or rainfall can minimize unnecessary operational costs and improve energy yield. Regular, tailored weather and climate services would enable the national electricity company (SENELEC), the renewable energy agency, and independent power producers (IPPs) to optimize resource management, production schedules, and maintenance planning, ultimately enhancing system reliability.

- **Institutional Coordination and Data Access**

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A major barrier identified is the limited coordination and weak communication between key institutions, including SENELEC, the National Agency for Renewable Energy (ANER), and the National Meteorological Office (ANACIM). While NFCS provides a formal mechanism for engagement, interactions remain largely ad hoc and request driven. The energy stakeholders expressed a need for a sector-specific framework, formalized conventions, and memoranda of understanding to facilitate routine access to weather and climate services. Furthermore, several IPPs are interested in establishing collaborations with ANACIM. Such partnerships with IPPs could not only enhance operational decision-making for the energy sector but also create potential revenue streams for ANACIM, supporting the sustainability of its services. Enhancing interagency collaboration and establishing formal partnerships can reduce reliance on online weather and climate information providers and strengthen the national climate services framework. Policy makers should prioritize mechanisms that formalize data sharing and ensure the regular dissemination of weather and climate information tailored to energy sector requirements.

- **Expanding Communication Channels**

Current dissemination of weather and climate information is predominantly through email, social networks, and national TV broadcasts, limiting timely access for operational decision-making. Although ANACIM employs multiple platforms, including Geoportal, websites, social networks, SMS alerts, and community radio (for farmers and fishermen), the energy sector would benefit from direct and advanced notifications. Implementing targeted communication channels, such as subscription-based alerts or integrated dashboards for the energy sector, could enhance responsiveness to short-term weather events and improve planning for extreme conditions. Lessons can be drawn from other sectors, such as agriculture, where SMS-based Early Warning Systems (EWSs) in local languages have improved outreach and actionability.

- **Building Resilience and Adaptation Capacity**

Adaptation strategies are essential for mitigating the impacts of climate extremes. The study revealed that renewable energy plants incorporate preventive maintenance, extreme-weather-proof design, and equipment upgrades. However, a comprehensive, sector-wide resilience plan is lacking. According to participants, practical steps include diversifying the energy mix, stabilizing grid operations, and coordinating infrastructure and operational responses across institutions. Policy makers and plant operators can jointly develop resilience strategies, emergency response plans, and technology adaptation guidelines, ensuring continuity of energy production under variable climatic conditions. Weather and climate services can strengthen these resilient efforts by providing tailored forecasts, early-warning information, and climate-risk assessments that support operational and investment decisions. Short-term weather forecasts can support grid stability by helping operators anticipate renewable generation fluctuations, allowing load management and network protection. By integrating weather and climate services into planning, plant operators can anticipate extreme events, optimize maintenance schedules, adjust operational strategies to reduce weather-induced losses, and enhance long-term adaptation capacity.

- **Policy and Investment Implications**

The findings suggest priorities for policymakers and practitioners. First, strengthening NFCS implementation for the energy sector through dedicated funding, capacity building, and institutional support is essential. Second, fostering collaboration between government agencies, IPPs, and ANACIM can improve access to weather and climate services and operational planning. Third, targeted investment in communication infrastructure and digital platforms will enable real-time dissemination of climate information tailored to energy needs. These measures can reduce operational risks, enhance energy security, and support Senegal's transition to a resilient, clean energy system.

In conclusion, this study demonstrates that weather and climate services are essential for informed decision-making in the energy sector. By addressing institutional, technical, and communication barriers, climate information can be harnessed to optimize energy production, improve operational efficiency, and strengthen resilience against climate variability and change. The insights from this study provide a roadmap for integrating weather and climate services into energy sector planning, offering practical guidance for government, policymakers, regulators, and practitioners.

1. Introduction

Climate change poses a significant threat to developing countries, impacting their socio-economic stability and environmental sustainability. Addressing this challenge necessitates prompt actions to lower greenhouse gas emissions and adapt to the inevitable changes already taking place (Cortekar et al., 2020). To achieve this, weather and climate services play a significant role in enabling climate-informed decision-making across both public and private sectors (Cortekar et al., 2020). An important and growing demand exists for high-quality climate information to enhance decision-making, support adaptation and mitigation efforts, and build resilience across all sectors (Findlater et al., 2021). This demand has led to the rapid expansion of the climate services field, which fundamentally aims to deliver weather and climate information essential for informed planning (Vogel et al., 2019).

In the context of energy systems, the variability and changes in weather and climate have significant impacts. Several studies have demonstrated the effects of climate change on energy in general (Mideksa and Kallbekken, 2010; Schaeffer et al., 2012; Ciscar and Dowling, 2014; Troccoli et al., 2018), and renewable energy in particular (Fant et al., 2016; Huber et al., 2016; Müller et al., 2019; Sawadogo et al., 2021; Ogunjobi et al., 2022; Danso et al., 2022; Ndiaye et al., 2022). As the energy sector deals with these challenges, the role of tailored weather and climate services becomes increasingly important. Climate services play a crucial role in helping adapt to these challenges by providing essential information and tools for effective decision-making and resilience building.

Efficient planning and operation of energy services across diverse scales require robust weather and climate information. This is especially crucial given the anticipated surge in global energy demand and the interdependence between weather, climate, and energy systems (Gunasekera, 2018). The energy sector is known to be very vulnerable to weather and climate. Renewable energy systems depend heavily on weather and climate conditions; the transition to clean energy requires enhanced climate information and tailored climate services for the energy sector (WMO, 2022). Thus, appropriate weather and climate services are needed to help minimize the negative impacts in the sector.

Weather and climate services are decision-support tools developed through the transformation of weather and climate information into tailored advisory products that help individuals and organizations make informed decisions (Tall et al., 2018). Weather and climate services aim to deliver timely and tailored climate knowledge and information, enabling individuals and organizations to minimize climate-related risks and maximize potential benefits (Vaughan and Dessai, 2014). This entails not only forecasting weather patterns but also translating data into practical guidance for diverse sectors. Integrating these insights empowers stakeholders to make informed decisions, improve preparedness, and respond effectively to climate impacts. Access to reliable climate information is fundamental for enhancing societal resilience against a changing climate (Christel et al., 2018). It allows for the anticipation and mitigation of risks linked to climate variability and change while also enhancing the ability to leverage emerging opportunities (Goddard, 2016).

Although the energy sector is among the most advanced users of weather and climate information, its rapid transformation continuously generates new demands, necessitating a more effective collaboration between meteorologists and energy sector users (Dubus et al., 2018). Scientific progress alone cannot enhance the value of weather forecasts. Increasing their usefulness for decision-making also requires improved communication and mutual understanding between meteorologists and energy stakeholders (Dubus et al., 2018). The demand for weather and climate information in the energy sector is increasing across many regions of the world. Effectively delivering such information requires sustained interactions with users throughout the entire energy supply chain (Gunasekera, 2018).

In recent years, climate services have evolved with advanced progress in terms of research. In Europe, according to Bruno Soares et al. (2018), few studies have focused on climate services providers and the climate information and tools produced (e.g., Máñez et al., 2014; Banos de Ghisasola, 2014; Cortekar et al., 2020), or the climate information needs of the end-users (e.g., Turnpenny et al., 2004; Dessai and Bruno Soares, 2015; Tart et al., 2020). In Africa, climate services research addresses a range of critical issues to enhance the provision and effectiveness of climate information across the continent. Steynor and Pasquini (2022) investigated the efficacy of current climate services in East Africa, emphasizing the importance of understanding climate change risk perceptions. Lamptey et al. (2024) discussed the challenges and potential pathways for developing sustainable weather and climate services in Africa. In their study, Vogel et al. (2019) provided a commentary on efforts to ensure inclusive, robust, and sustainable climate services, critically assessing current activities and their impact. Dinku et al. (2022) introduced the Climate Data Tool, an open-source software designed to enhance climate services by facilitating data organization, quality control, and comprehensive analysis. Additionally, research emphasizes the importance of assessing user needs for climate information, particularly in West Africa and Senegal (Sultan et al., 2020). Furthermore, Meque et al. (2021) explored the challenges and opportunities for improving climate services delivery in Southern Africa, highlighting areas for growth and development. Several studies also concentrate on the agricultural sector, emphasizing the importance of climate information in enhancing agricultural productivity and resilience (Roudier et al., 2012; Mabe et al., 2014; Zongo et al., 2014; Bayala et al., 2017; Dayamba et al., 2018; Tall et al., 2018; Hansen et al., 2019; Antwi-Agyei et al., 2021; etc.). However, studies to assess the impact of weather and climate services and determine the value of these services for the energy sector are very few, if not nonexistent, in Africa. In this context, case studies provide valuable insights into how weather and climate services are implemented and how they can be improved within institutions.

This study presents a qualitative case study of the provision and dissemination of weather and climate services in the energy sector in Senegal. It aims to assess how these services are provided, disseminated, and used, in order to identify sector-specific needs and the potential gaps between the national meteorological office and energy sector stakeholders. This assessment is carried out in the context of Senegal's national framework for climate services (NFCS), which was ratified in 2016. While other sectors, such as agriculture and fisheries, have made progress under the NFCS, the energy sector has seen limited implementation, a gap this study aims to explore. This case study provides context-specific insights into the challenges and opportunities of integrating weather and climate services into the energy sector. The energy sector refers here to the electric energy or power sector, which is a mix of thermal and renewable energy (solar, wind, and hydro). In this study, we will only consider the thermal plants operated by SENELEC, wind, and solar power plants.

2. Data and Methodology

2.1. Energy Profile in Senegal

In Senegal, the energy sector is constituted mainly by the National Electricity Company (SENELEC), which oversees the production, distribution, and commercialization of electricity in urban areas. The Senegalese Rural Electrification Agency (ASER) is an independent operational unit under Senegal's Ministry of Energy, responsible for promoting rural electrification through support for initiatives at the national and international levels. The National Agency for Renewable Energy (ANER) is a government agency that has as mission to promote the use of renewable energies, including bioenergy, in all sectors of activity, but also to identify, assess, and exploit the potential of renewable energy exploitable in the different regions of the country. Besides this, Senegal currently has nine (9) operational IPPs in renewable energy (Fig. 1.a). The nine comprise eight (8) solar plants with an installed capacity greater than or equal to 20 MW each and one wind farm with an installed capacity of 158 MW. The solar IPPs are located in Bokhol, Sakal, Malicounda, Ten Merina, Santiou Mekhe, Kahone1 (Energy Resources), Kahone2 (Solarsen), and Kael. The wind farm is located in Taiba Ndiaye. The IPPs, both in renewable and thermal, constitute 50.6% of the total installed capacity of SENELEC (about 1800 MW), in 2023 (Fig. 1.b). All the IPPs are directly connected to the SENELEC network, which buys the electricity produced. The Ndiass solar plant is the only photovoltaic plant owned by SENELEC.

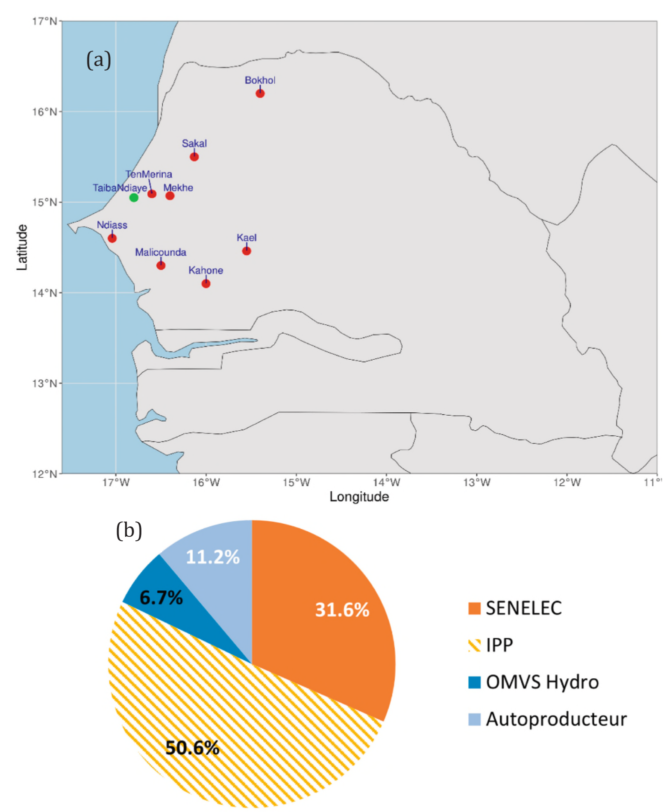

Fig. 1. (a) Senegal map with the locations of the solar plants (red) and wind farm (green). (b) Distribution of installed electricity capacity in Senegal in 2023. IPPs supply more than half of the capacity, followed by SENELEC – (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Source: Senegal Electricity Sector Master Plan 2024-2040 (September 2024)

2.2. Semi-structured interviews of experts

The data for this study were collected through semi-structured interviews with experts in both the energy and the meteorological sectors of Senegal. A semi-structured interview was used to allow open-ended responses to provide much more information about the questions. Semi-structured interviews are an effective method for data collection when the researcher wants: (1) to collect qualitative, open-ended data; and (2) to explore participants' thoughts, feelings, and beliefs about a particular topic (Mashuri et al., 2022). It allows interaction between the interviewer and the respondent, where the latter most likely opens up and provides information beyond the question asked.

The different steps required in an interview process are shown in Fig. 2. In the first step, the design establishes the interview guide. It defines the objectives and core questions and selects the type of interview. The data collection phase involves participant sampling, conducting interviews, and taking notes. Finally, the data analysis phase includes transcribing the recordings, coding themes, and interpreting findings to draw conclusions.

A total of 17 experts were interviewed in 2021: thirteen were face-to-face, two via email, and two were online Zoom meetings because of COVID-19. The experts are distributed by institutions: three at the national meteorological office, two at SENELEC, two at ANER, two at Ten Merina solar plants, and the remaining are one per IPP. Out of eight solar plants, a total of seven were interviewed. One expert from the regional office of GFCS was also interviewed to find out about the state of the NFCS. The number of expert interviews conducted was limited, which may not fully capture the diversity of perspectives within the energy sector in Senegal. However, the experts interviewed occupied high positions in the institutes (Table 1), which are likely to have provided valuable and informed insights that reflect the sector's strategic and operational priorities.

A semi-structured guide of about forty questions was developed (Appendix 1). All the questions revolve around the same subject, namely: an introductory part, the communication framework, the type of weather and climate services received on the energy sector side (produced on the meteorological side), the early warning system, and legislation. In the introductory part, questions asked were about the experts and their expertise, the role and responsibilities of the institutions, and the installed capacity of the plants, among others. The interview took roughly thirty (30) minutes to one hour. Notes were taken, and audio recordings were made with the consent of the respondents. The national language of Senegal being French, all the transcriptions were translated into English by taking into account the accuracy of the words used. Efforts were made as much as possible to conserve the meaning of the original words.

Table 1
Profile of the respondents.

Type of occupation	Institutions	Plant Type	Number
Technical Advisor to the Director General of ANER	ANER	–	1
Engineer, Projects, and Programs Department	ANER	–	1
Director of Meteorological Operations	ANACIM	–	1
Head of the meteorological information system, Department of Meteorological Operations.	ANACIM	–	1
Head of the Climatology and Climate Services, Research and Development department.	ANACIM	–	1
Site manager and plant operations manager	Bokhol	Solar	1
Plant Operations Manager	Kahone1/ Energy Resources	Solar	1
Plant Engineer	Malicounda	Solar	1
Regional expert of the Global Framework for Climate Services	GFCS	–	1
Business Manager of the plant	Ten Merina	Solar	1
Technical manager of the plant	Ten Merina	Solar	1
Business Manager of the plant	Kael	Solar	1
Plant Manager	Taiba Ndiaye	Wind	1
Business Manager of the plant	Kahone2/ Solarsen	Solar	1
Business Manager	Mekhe	Solar	1
Forecasting Expert, Electrical System Operation	SENELEC	Conventional & Renewable	1
Head of Research and Demand Management	SENELEC	Conventional & Renewable	1

2.3. Data analysis

Since semi-structured interviews were used, the respondents' answers were not straightforward to analyze. Therefore, a data analysis method known as thematic analysis was employed to identify patterns (themes) within the data (Maguire and Delahunt, 2017). This method is valued for its theoretical flexibility and utility as a research tool, allowing for a rich and detailed analysis of the data (Braun and Clarke, 2006). Interview data were thematically coded into categories using NVivo 12.6 to identify patterns and construct a structured analytical framework, creating a new structure for the data (Bazeley and Jackson, 2014). This process reorganized raw data into themes and subthemes, enabling systematic comparison across participant responses.

This approach of qualitative coding using NVivo software has been used by many studies (Bruno Soares and Dessai, 2016; Vaughan et al., 2017; Bruno Soares et al., 2018; Daly and Dilling, 2019; Clifford et al., 2020; Findlater et al., 2021; Steynor and Pasquini, 2022).

An inductive approach, which is a data-driven approach to coding the data and identifying themes focusing on the semantic content of the data, was used (Chandra and Shang, 2019). A theme captures something important about the data in relation to the research question and represents some level of patterned response or meaning within the dataset.

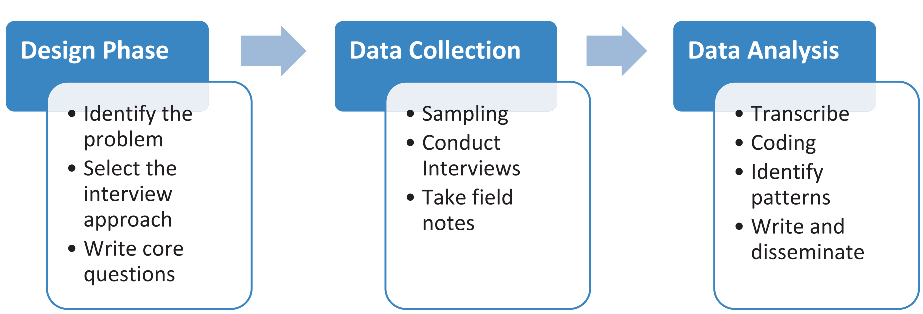

Fig. 2. The key steps of an interview process . adopted from (Larosa and Mysiak, 2020)

The detailed approach and the step-by-step analysis method can be found in Fig. 3.

3. Qualitative findings

The interview revealed nine themes identified from the analysis (Fig. 4). These themes are presented and analyzed in the next sections.

3.1. The global and national framework for climate services (GFCS, NFCS)

The GFCS and the NFCS provide crucial structures for organizing and implementing climate services. GFCS serves as a global guideline for countries to collaborate on climate change adaptation and mitigation, among others, while NFCS adapts these global principles to the national context, involving local actors in defining strategic plans and actions. Senegal's NFCS, ratified in 2016, incorporates six priority sectors: health, agriculture, water resources, energy, disaster risk reduction, and tourism, with ANACIM leading the coordination efforts. Significant progress has been made in specific sectors, particularly agriculture and fisheries. These sectors have benefited from numerous activities, including capacity-building workshops and the issuance of climate bulletins. In Senegal, agro-hydro-meteorological monitoring of crops and pastures is coordinated by a Multidisciplinary Working Group (MWG) led by ANACIM. This group includes representatives from key technical sectors involved in agricultural production. With the establishment of the NFCS, the MWG has expanded to include the health sector and the media. Every ten days, the MWG collects and analyzes climate and hydrological data and information on crop conditions, pasture status, and food security. The findings are compiled into a ten-day Agro-Hydro-Meteorological bulletin, which informs decision-making by political, administrative, and technical authorities to support timely and appropriate responses. The MWG has been effective during the rainy seasons, demonstrating how targeted interventions can support sector-specific needs. As one participant noted, *"Agriculture and fisheries are the most dynamic sectors of the framework because they have been able to benefit from several activities: capacity-building workshops, bulletins, among others"*.

The NFCS framework has also facilitated the creation of strategic and action plans tailored to Senegal's needs, reflecting a structured approach to tackling climate impacts. Efforts are underway to define activities and indicators for each sector, as indicated by the interview extract: *"Now what the NFCS is trying to do with all the other sectors is to define groups of activities for each sector to carry out the services and identify indicators and develop bulletins"*.

However, challenges persist, particularly in sectors such as energy, which have not seen significant benefits from the NFCS. According to the participants, while some sectors have benefited, the progress in others remains slow. In the energy sector, they noted a lack of awareness of any ongoing activities. This disparity highlights the need for more efforts and resources in these underrepresented sectors. Funding and administrative issues have also slowed the pace of project implementation. The absence of a Prime Minister's office in Senegal (2019–2021) has particularly affected progress, as one participant described: *"Currently, it is slow to implement projects on the ground, and it is due to a lack of funding. Also, for the case of Senegal, although we have the decree of the Prime Minister's office signed to validate the NFCS, Senegal no longer has a Prime Minister's office."* The GFCS has faced challenges that have led to delays in planned activities. As a participant from the energy sector mentioned, *"There has been no real progress with the GFCS. Projects have been budgeted, but after the budgets have their realities, they were not finalized"*.

Efforts to address these challenges include expanding coordination among sectors to enhance the integration of weather and climate services. ANACIM is working on expanding MWG's involvement to all priority sectors, aiming to improve information exchange and service delivery. This is crucial for fostering a unified approach, as emphasized by the participant who said, *"ANACIM is working on how to expand the MWG to all sectors so that in the working group meetings they can all give complementary information regarding the sectors to exchange so that the system is more unified"*.

To improve the situation, addressing funding constraints is essential. Securing financial resources for NFCS activities should be a priority, and exploring alternative funding sources could help overcome budgetary challenges. Capacity building in underrepresented sectors, such as

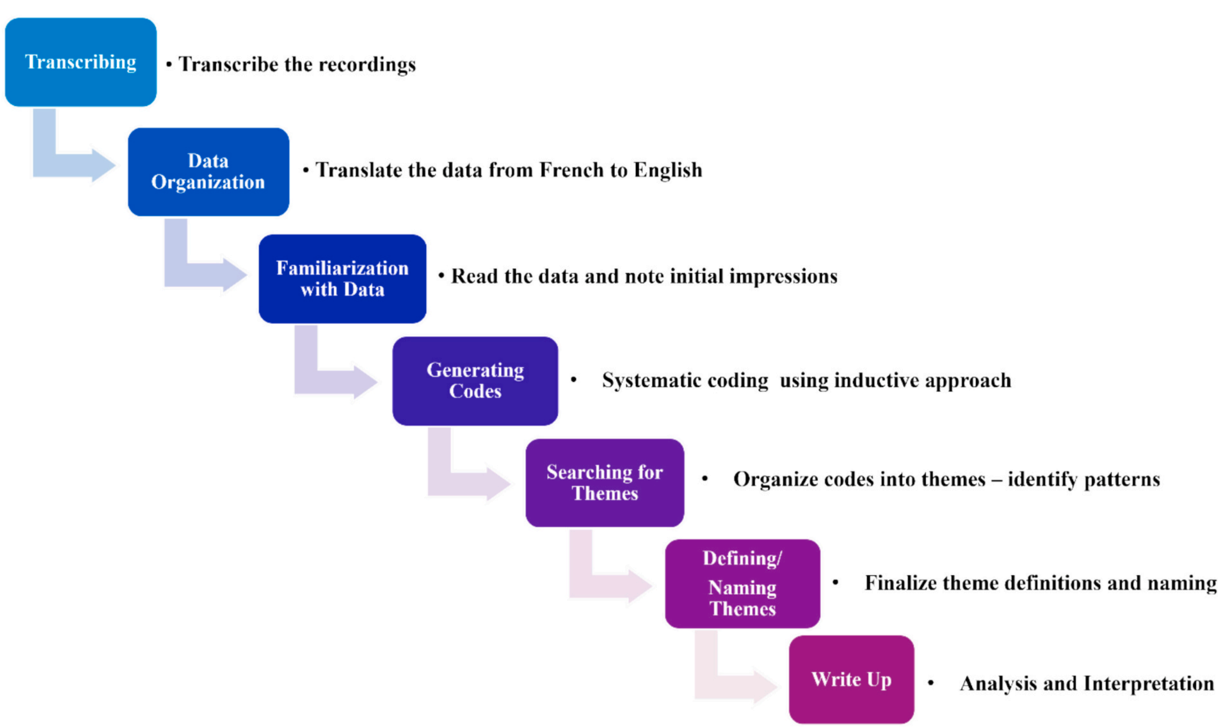

Fig. 3. Phases of the Thematic Analysis applied to our research and adopted from (Braun and Clarke, 2006).

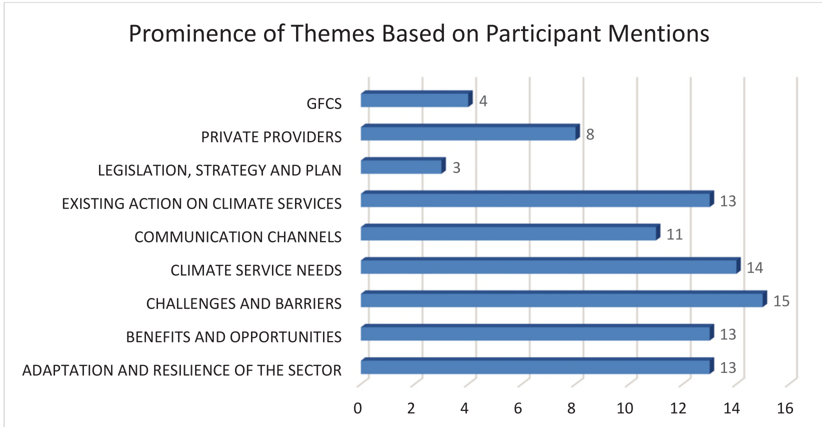

Fig. 4. Main themes identified in thematic analysis and their participant coverage.

energy, is also critical. Developing targeted training and awareness programs can better meet the sector-specific needs and enhance the effective use of weather and climate services.

Expanding sectoral involvement and strengthening national and regional collaboration can enhance the effectiveness of the NFCS. Improved collaboration, along with robust monitoring and evaluation mechanisms, will be essential for assessing the impact and efficacy of NFCS activities. As noted in the interviews, *"It is necessary to define with these sectors' activities to implement bulletins, capacity building, organize consultation workshops, etc., so that all sectors work in relation to a common coordinator, as ANACIM is the lead of the activities of the framework"*.

3.2. Benefits and opportunities

The impact of weather and climate on the energy sector is of central concern, particularly regarding production and use. Participants in the interviews were unanimous in their acknowledgement of how climate variables can affect the energy sector. These impacts are particularly pronounced in renewable energy, which is becoming a significant component of Senegal's energy mix. Specific examples provided by interviewees illustrate how weather and climate affect energy production. For instance, wind patterns play a crucial role in the efficiency of wind turbines. As noted by an interviewee, *"We receive information about wind, and it has, of course, an impact on production, no wind, no production. We have very weak production during the hot season because of low wind speed. But also, our biggest concern is the extreme wind speeds. The turbine stops automatically at 21 m/s (for safety reasons)"*. This statement reflects how seasonal wind variations can significantly impact energy production from a wind farm. Similarly, temperature variations can affect the efficiency of solar panels. In hotter areas, such as the northern parts of Senegal, the efficiency of solar panels is compromised. Weather and climate also influence other aspects of energy production. As one interviewee explained, *"wind has a direct impact on wind production and supply, and precipitation also impacts hydroelectricity production, as well as agricultural and leaf yields when looking at biomass (bioenergy)."* This comprehensive view shows the interconnected nature of weather and climate impacts across different renewable energy sources.

With renewable energy accounting for about 500 MW of the total installed capacity of about 1700 MW in 2023 in Senegal's national electricity company, understanding and managing these impacts is crucial. One participant stated that the growing recognition of climate service needs is evident: *"It is a need, it is an input, people are more and more in agreement with this fact."* This sentiment reflects a broader acceptance of the necessity for incorporating climate information into energy sector planning and operations.

The integration of climate information into the energy sector offers several benefits and opportunities, as highlighted by a solar energy respondent: *"We clean the plant once a month, but sometimes it happens that just after cleaning, there is a sandstorm, and we will be forced to clean again; otherwise, we will not be optimizing production. So, we need to collaborate with ANACIM. We shouldn't have cleaned up if we knew there would be a sandstorm, which is an additional burden on operating costs"*.

Stakeholders can develop more resilient and adaptive strategies by better understanding how climate variables impact energy production. For instance, improving forecasting methods for wind and solar resources can enhance the efficiency and reliability of renewable energy sources. The benefits and opportunities of integrating weather and climate information into the energy sector are significant. As the interview extracts reveal, acknowledging and addressing the impacts of climate parameters on renewable energy sources is essential for optimizing production. The growing consensus on the need for climate data underscores the importance of developing strategies that leverage this information to enhance the resilience of the energy sector. The different benefits of climate data and services highlighted by the experts are given in Fig. 5.

3.3. Challenges and barriers

The experts have highlighted several challenges in integrating weather and climate services within the energy sector, particularly the lack of convention and a weak communication framework between key government institutions such as SENELEC, ANER, and ANACIM. Although these institutions are formally connected through the NFCS, the framework represents the initial mechanism for dialogue and exchange among them. However, participants from the energy sector stressed that these exchanges need to be further developed to meet the sector's specific needs. As one participant remarked, *"There is an official NFCS communication framework, but we would like to go much further and*

Fig. 5. Benefits of weather and climate services according to the participants.

perhaps have bilateral collaboration for the needs of the energy sector and renewable energy in particular".

Energy experts also highlighted a critical need for a sector-specific exchange framework, emphasizing that the sector has specific needs that should be addressed separately. The energy sector seeks not only to use the currently produced information but also desires a specific framework to govern all its needs. This was raised in the interviews: *"Formally, we are connected to the energy sector through this framework, we have been working with SENELEC for quite some time, and we have been in discussions for the signing of a memorandum of understanding (MoU) because they need us to provide them with climate information regularly."* This illustrates the necessity for formalized agreements to facilitate regular provision and access to climate information. Another expert underscored the importance of creating conventions between government agencies to streamline access to necessary data: *"It would be important to make a convention between the agencies. We have to try to work together between government departments so that we can have access to this information. The convention can allow us to access certain data and information without writing and asking all the time."* This indicates the potential benefits of establishing formal conventions to enhance inter-agency cooperation and data sharing.

Challenges remain despite ongoing discussions about partnerships, such as the one mentioned with ANACIM. *"Discussions are underway to partner with ANACIM for the provision of climate data and information regularly."* This statement highlighted the slow progress and the need for more concrete actions to establish these partnerships. Additionally, there is a notable lack of collaboration between IPPs and the national meteorological office. None of the eight IPPs, seven solar plants, and one wind farm reported collaborating with ANACIM, instead relying on private providers for climate information. One participant admitted, *"However, we did not try to approach ANACIM; we just use the listed platforms."* Some IPPs even signed contracts with foreign institutions for daily weather forecasts, indicating a gap in local collaboration and use of national meteorological services. However, there is an expressed interest among some IPPs in establishing collaboration with ANACIM for multiple purposes, suggesting an opportunity for developing these relationships.

3.4. Identified needs in weather and climate services

The participants in the energy sector highlighted specific needs for weather and climate services, including short-term forecasts and sub-seasonal and seasonal forecasts of different variables (Table 2). Preferred lead times range from daily to decades, depending on the application. These requirements reflect practical needs for generation planning and operational risk management.

Table 2
Identified weather and climate services needs from the energy sector participants.

Variables	Services	Lead Time	Use Case
Solar radiation, temperature, humidity, wind speed	Weather forecast	Day ahead	Day-ahead generation, Load balance and management
Cloud cover	Weather forecast	Day ahead	Day-ahead generation, PV output estimation
Strong wind	Sub-seasonal climate forecast	Weeks ahead	Avoid operational risks, turbine safety or lifting of panels
Heavy precipitation	Sub-seasonal climate forecast	Weeks ahead	Maintenance and cleaning schedule
Sandstorms	Sub-seasonal climate forecast	Weeks ahead	Cleaning and operational safety
Solar radiation, temperature, precipitation, wind speed	Seasonal climate forecast	Months ahead	Seasonal generation planning, maintenance planning
Solar radiation, temperature, precipitation, wind speed	Climate projections	Decades ahead	Long-term planning, resource planning

3.5. Existing action on climate services

Despite the challenges in obtaining weather and climate services for the energy sector in Senegal, there are several instances of information exchange between government institutions and ANACIM. However, this exchange often occurs upon request rather than on a regular basis. One participant highlighted this by stating, *"In the past, we had to work with certain structures such as ANER, SENELEC, which always make requests, and for the moment we are responding on an ad hoc basis concerning these requests, but we have not yet considered in relation to the routine to think about new products. This products/information are supplied according to demand."* This ad hoc provision indicates a lack of a systematic approach to climate information dissemination. The irregularity of receiving climate information is also a concern, as one interviewee pointed out, "*We do not receive climate information on a daily or monthly basis; there is no fixed frequency."* This lack of regular updates can hinder the energy sector's ability to make informed decisions based on timely weather and climate services.

Most of the services requested by the energy sector from ANACIM include alerts, forecasts, predictions, and projections on key climate parameters such as temperature, humidity, wind, and rainfall. While the information provided is considered informative, there is a desire to strengthen the relationship to ensure regular and tailored services. Participants expressed general satisfaction but emphasized the need for more consistent engagement.

According to ANACIM, they produce a wealth of information that could benefit the energy sector. This includes seasonal forecasts on rainfall and temperature, and weather forecasts (24 h, 48 h, 72 h) on rainfall, temperature, wind, and solar radiation. This information could help the sector anticipate weather changes. Additionally, ANACIM makes long-term climate projections, such as impact studies for specific localities up to 2030, to predict changes in temperature or rainfall. This data is crucial for strategic planning and adaptation measures within the energy sector. Extreme climate forecasts are also available, particularly during the rainy season, covering heavy rainfall, heat waves, and droughts. ANACIM provides EWSs for extreme weather phenomena like heavy rain and wind gusts. Although these EWSs are issued based on the existence of the products, as one participant noted, *"The frequency of the delivery is on an ad hoc basis because it depends on the existence of the products"*.

Currently, there is no centralized mechanism to coordinate all EWSs, which include alerts for flood risks, agriculture, and fishing. However, there are developments towards establishing a national EWS through the Operational Center for Interministerial Crisis and Disaster Management (COGIC), led by the Directorate of Civil Protection. Notably, the EWSs for agriculture and fishing are well-developed and disseminated via SMS and in local languages, demonstrating a model that could be replicated for the energy sector.

3.6. Communication channels

The communication channels used for disseminating weather and climate services between government institutions and ANACIM are primarily centered around email. The type of services provided can vary, encompassing both reports and raw data. One participant highlighted this: *"We do periodic reports, but it depends on the type of request we receive. Some requests require raw data, so we provide them in Excel format, while others need a report, and in this case, we provide these reports."* ANACIM also provides EWSs through bulletins, vigilance maps, or SMS alerts. However, the energy sector typically receives these alerts through national TV broadcasts. The use of television for disseminating crucial alerts suggests a need for more direct and diverse communication channels to ensure timely information delivery. The energy sector, including SENELEC, ANER, and IPPs, often receives alerts only through TV broadcasts of ANACIM, as highlighted by the participants. This limited mode of communication indicates a gap in the direct and timely dissemination of critical climate information. Establishing more direct communication channels could significantly enhance the sector's ability to respond to and mitigate the climate impacts.

"It would be good if we could get personalized service from ANACIM, which would give us the information a week in advance. Because with the announcements that are shown on TV, the time is usually very short, the information usually passes the day before".

"Also, we can decide to clean the panels, but if it rains, we will no longer need to do this. If we know in advance that there will be rainfall during the week, we can take this into account so as not to disrupt our schedule ".

According to ANACIM participants, the institutions use multiple channels to disseminate climate information, ensuring broad accessibility and coverage. These include Geoportal, the national framework portal, the ANACIM website, social networks, radios, and televisions. Their extensive collaboration with the "Union des Radios Communautaires", which encompasses over 120 community radio stations, shows a commitment to reaching a broad audience. Furthermore, ANACIM engages in public–private partnerships and collaborates with start-ups to enhance their digital communication capabilities.

3.7. Private providers

Fig. 6 illustrates the sources of weather and climate services for energy sector stakeholders. The majority of the IPPs rely on free online platforms and software to meet their weather and climate service needs. One IPP is under contract with a foreign company to receive the necessary daily forecasts. In addition to the information provided to government institutions upon request, these online platforms are heavily used to complement ANACIM's products, particularly for daily estimates of climate parameters. Some commonly used platforms and software include Meteomatics, PVGIS, wunderground.com, weatherchannel.com, and weather2umbrella.com. These tools are often used for weather prediction and production forecasts. One participant highlighted their utility: *"In addition, for production forecasts, the website is consulted to find out if there will be clear skies in the coming days, as well as temperature and wind speed. Depending on that, we can roughly know how much we will produce during this period".*

Most IPPs expressed satisfaction with these platforms, as reflected in an energy expert's comment: *"It's ok, the forecasts are pretty good since we've been using the platform."* However, there are still limitations to these services, and several IPPs wish to have better alternatives. About four IPPs noted the shortcomings of these platforms and expressed a desire for improved services. One expert mentioned frequently consulting the ANACIM website for complementary information, stating, *"Usually, I visit the ANACIM website to get information about the forecasts".*

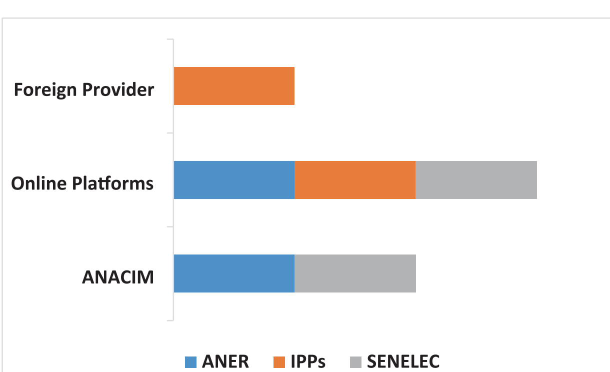

Fig. 6. Provision of weather and climate services to energy stakeholders in Senegal.

The reliance on satellite data, which is not always reliable, underscores the need for better alternatives. As one participant explained, *"It is satellite data, therefore not 100% reliable, but since we have no other alternatives, we are obliged to use it. We wish to have better, if possible."* This sentiment is shared by others who value collaborating with ANACIM to access more accurate data. Another participant emphasized, *"It would be interesting to exchange with ANACIM because they are the ones who have the most accurate data."* This collaboration could help resolve discrepancies in precipitation forecasts, which are often significant. One expert elaborated, *"At the plant, we have local stations, but sometimes it is necessary to collaborate with ANACIM to make a comparison with the data, especially the precipitation part. Sometimes our forecasts are very different from those of ANACIM".*

3.8. Adaptation and resilience in the energy sector

Climate change poses a significant threat to various development sectors, and the energy sector is no exception. All participants emphasized the importance of having an action plan for adaptation and resilience. They unanimously expressed confidence in their resilience and adaptation strategies to climate extremes. For instance, government institutions conduct annual assessments of their projects to evaluate effectiveness and identify areas for improvement. One participant mentioned, *"In our first projects, we used lead batteries for storage, but now we use lithium batteries. We try to improve every year. Also, with extreme temperatures, you have low solar production. That's why we always try to use the best panels in the market."* These evaluations aim to enhance future projects by learning from past experiences. Additionally, there is a recognized need for more human and technical resources, including advanced modelling tools, to better account for climate extremes and their impacts on the sector.

The IPPs emphasized that their solar plants were appropriately sized to withstand climatic conditions, with these factors integrated during the planning and design phase. Assessments included soil resistivity, selection of panel materials, and the potential impacts of weather and climate extremes such as heavy rainfall, intense solar radiation variations, and strong winds. As mentioned by one interviewee, *"Climate extremes are considered because the plant is sited to the most unfavorable conditions. Usually, we consider the hottest months with extreme irradiation. We resist strong winds which have not yet happened to us."* Despite these precautions, some incidents involving wind lifting solar panels occurred during the early stages of operation, as mentioned by one respondent. One participant noted that heavy rainfall affected road access, which kept them from doing maintenance, but the production was not affected. Moreover, there is no defined resilience plan across all plants. But multiple actions are in place to ensure resilience. Preventive maintenance is a crucial part of device monitoring, and the proposal of new technologies adapted to future climatic conditions is considered. Extreme heat or temperature variations can significantly reduce the lifespan of PV panels due to cell degradation, necessitating a stock of spare parts modulated according to climatic variations. Some plants have sensors that shut down machines when temperatures reach extreme levels to maintain normal operating conditions.

4. Discussion

The integration of weather and climate services into the energy sector is increasingly recognized as essential to addressing the challenges posed by climate variability and change. Weather and climate services provide the necessary information to better manage climate risks and variability, and they are critical to optimizing decision-making in the energy sector. Studies from various regions show that sector-specific climate services can significantly enhance resilience and adaptive capacity in changing climate conditions (Vincent et al., 2018; Bruno Soares et al., 2018).

The establishment of the GFCS and the NFCS demonstrates a global and national commitment to mitigating the adverse effects of climate change (Hewitt et al., 2012; WMO, 2014). The GFCS aims to help society more effectively manage the risks and opportunities posed by climate variability and change by integrating scientifically based climate information and predictions into planning, policy, and practice (WMO, 2014). While the GFCS and NFCS frameworks provide a solid foundation for climate services in Senegal, addressing the identified challenges through enhanced coordination, funding, and capacity-building efforts is essential for optimizing their impact. The concrete examples provided in the interviews highlight both the progress made and the areas needing improvement, showing the need for focused efforts and strategic enhancements. In Senegal, the NFCS has identified the energy sector as a priority, recognizing the critical need for reliable climate information to support the sector's sustainable development.

However, despite this recognition, significant challenges remain, particularly related to communication and collaboration frameworks. Interviewees consistently reported gaps in the delivery of climate information. For example, several stakeholders mentioned that they receive general information on TV, which limits their operational use. While the current channels ensure broad dissemination, the sector's specific needs for timely and actionable information highlight the necessity for more targeted communication strategies. Based on this finding, establishing direct communication channels such as dedicated email lists, mobile applications, or secure online platforms would directly address the gap raised by interviewees and enhance the effectiveness of weather and climate services. This can ensure that crucial climate information reaches them promptly and efficiently, thereby improving the sector's resilience and adaptive capacity. Moreover, while the NFCS provides a foundational framework for communication between government institutions in the energy sector, interviewees also emphasized limited bilateral exchanges between ANACIM and certain energy stakeholders, including IPPs. Some of them described only ad hoc exchanges and communication when requesting specific data. The need for enhanced bilateral collaborations and sector-specific frameworks is evident. Establishing conventions and improving the exchange of climate information could address many of the existing challenges. Furthermore, fostering collaboration between IPPs and ANACIM responds to interview-based observation and could enhance the overall use of weather and climate information and services in the energy sector.

Similar challenges have been identified across Africa, where the inconsistent provision of climate services and limited collaboration between key stakeholders hinder the effective use of climate information (Antwi-Agyei et al., 2021; Dinku et al., 2022; Lamptey et al., 2024). Naab et al. (2019) observed that institutional challenges include poor collaboration between relevant stakeholders in producing climate information that prevents the mainstreaming of climate information in Ghana. The experiences reported by interviewees in Senegal align with these regional patterns, suggesting that the constraints observed in this study reflect broader systemic issues. This irregular communication and data provision issue is compounded by reliance on external, sometimes less accurate, platforms for climate information, which may not always align with local conditions. The challenge Africa is facing is that the substantial advancements in global weather and climate science and services, which have brought environmental and socio-economic benefits elsewhere, have not been equally realized across the continent. As a result, Africa lags behind other regions in leveraging these improvements for its development (Lamptey et al., 2024). To increase the use of climate information in organizational practices, it is essential to overcome barriers by enhancing understanding of climate information, improving coordination and standardization across sources, and addressing gaps in information provision (Bruno Soares et al., 2018).

Moreover, the ad hoc nature of weather and climate service provision reflects a broader challenge across sub-Saharan Africa, where weather and climate services are often reactive rather than proactive. Several interviewees explicitly described receiving information on request or on TV broadcast, illustrating the reactive nature of communication. This irregularity can hinder the proactive management of climate risks. A known challenge is the difficulty in obtaining data from the National Meteorological and Hydrological Services (NMHSs). The discussion and the need for advocacy for easy access to the available data that are not easily accessible have been going on for a long time (Lamptey et al., 2024).

To address this, it is essential to establish routine climate service provision that anticipates the needs of the energy sector, rather than merely responding to immediate demands (Troccoli et al., 2018). This recommendation directly stems from interviewees regarding non-routine data access and irregular services. The development of EWS and more comprehensive climate data tools for agriculture, as seen in some parts of Africa (Dinku et al., 2022), suggests that implementing similar tools for the energy sector could significantly enhance its capacity to manage climate risks.

Adaptation and resilience in the energy sector require more structured and proactive approaches. While the energy sector in Senegal has taken steps to consider climate factors in project design, gaps remain in resilience planning. The incident of wind lifting the solar panel from the tables illustrates the sector's vulnerability to extreme weather events, despite the precautions taken. Interviewees further explained that they often lack weather and climate risk information that could help anticipate such extreme events.

To strengthen the energy sector's resilience, it is crucial to develop more robust, sector-specific communication frameworks. This includes addressing the collaboration and communication shortcomings identified in the interviews, particularly the absence of timely, tailored, and regular information, and creating a mechanism for two-way exchanges between the national meteorological service and the energy stakeholders. Fostering stronger collaborations between the national meteorological office and the energy stakeholders and ensuring that climate information is timely and relevant to the sector's specific needs would help close the gap between information production and operational decision-making. As highlighted in a study in Southern Africa, improving climate service delivery requires addressing both the technological challenges of weather prediction and the institutional gaps that prevent the effective use of climate data (Meque et al., 2021). Another important point highlighted by the Intergovernmental Panel on Climate Change (IPCC, 2014) is the importance of robust institutional frameworks and stakeholder collaboration in effectively managing climate risks.

These findings provide a basis for identifying the main lessons emerging from this case study. They highlight both the strengths and the limitations of weather and climate service provision in the energy sector in Senegal. On the one hand, there is clear recognition among stakeholders of the importance of climate information for operational and strategic decision-making, and they express strong interest in tailored products. The availability of climate products and the willingness of the energy sector actors to engage with the ANACIM represent important opportunities for strengthening the use of weather and climate services. On the other hand, the provision of weather and climate services remains largely ad hoc, communication channels are not tailored to sectoral needs, and collaboration between key stakeholders is limited. Both institutional and operational improvements are required to enhance the effectiveness of weather and climate services in the energy sector. These lessons are closely linked to the nature and quality of interactions between stakeholders, which play a central role in how weather and climate services are produced, communicated, and used.

The results are strongly informed by stakeholder interactions, which reveal important dynamics between climate information producers and energy users. While a wide range of climate information is available, its use is constrained by limited direct communication, irregular exchanges, and the absence of structured collaboration mechanisms. Strengthening engagement between stakeholders, including the establishment of formal agreements and regular communication channels, is essential to improve the delivery and use of weather and climate services.

While the findings of this study are specific to Senegal, they reflect challenges that are common in many countries in sub-Saharan Africa. Therefore, this case study provides relevant insights that can inform the development of weather and climate services in other countries in sub-Saharan Africa with similar institutional contexts and comparable structures and constraints.

5. Summary and conclusion

This study assesses the state of weather and climate services for the energy sector in Senegal. It highlights the progress and gaps in integrating climate services into Senegal's energy sector, based on evidence derived from stakeholder interviews and institutional analysis. The NFCS has supported beneficial exchanges of climate information between ANACIM and government institutions. However, there is a clear need for more regular and tailored dissemination of weather and climate services to the energy sector. The irregular provision of climate information, the lack of a sector-specific communication framework, the lack of collaboration with the IPPs, and the reliance on online platforms are barriers that need to be addressed, as identified through stakeholder experiences in this case study. Strengthening communication frameworks, establishing conventions, developing routine weather and climate service provision, and enhancing collaboration between key institutions can further improve the sector's resilience. While free online platforms and software currently fulfil the weather and climate service needs of many IPPs, there is a clear interest in more reliable data and climate information. The collaboration with ANACIM offers an opportunity to address the climate information needs, providing IPPs access to accurate data and climate information tailored to local conditions.

The way forward involves not only improving the existing frameworks and services but also fostering a more collaborative and integrated approach to climate resilience. Strengthening institutional collaboration, improving communication frameworks, and ensuring regular access to weather and climate services are key to building a more resilient energy sector in Senegal. These steps are necessary for climate risk management but also essential for ensuring long-term energy security and sustainable development, within the context-specific conditions highlighted in this study. Although the findings are specific to Senegal, they offer relevant lessons for similar contexts in sub-Saharan Africa, where weather and climate services for the energy sector remain underdeveloped.

CRediT authorship contribution statement

Aissatou Ndiaye: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Data curation, Conceptualization. **Jan Bliefernicht:** Writing – review & editing, Visualization, Supervision, Conceptualization. **Benjamin Lamptey:** Writing – review & editing, Supervision, Conceptualization. **Harald Kunstmann:** Writing – review & editing, Supervision.

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Declaration of competing interest

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

Appendix 1

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Appendix 1. . Questionnaire

The following questionnaire was used in this study. The version used for ANACIM served as a baseline. Some questions in the energy sector version were adapted from this to reflect operational realities, and additional sector-specific questions (e.g., plant characteristics, resilience to extremes) were included.

Questionnaire for ANACIM

Introduction

1. Could you briefly introduce yourself?
2. Is your institution public or private?
3. Could you give a short description of your institution, its role and responsibilities?
4. What are the types of climate parameters you produce, and how many stations do you have?

Communication framework

5. Is there a communication framework between your institution and the energy sector?
   a. If yes, does the existing framework enable regular interaction? Is it appropriate?
   b. If not, did the energy sector request weather and climate services?
6. What types of weather and climate services are provided to the energy sector?
7. How is climate information delivered to the energy sector (reports, bulletins, maps, etc.)?
8. What communication channels are used (email, SMS, hard copy)? Are they appropriate?
9. Are there mechanisms for two-way dialogue/feedback with the energy sector?
10. Does your institution collect or receive feedback from users in the energy sector?
    a. If yes, what is the users' appreciation of the products?
    b. If not, do you plan to collect feedback?
11. Do you know how the energy sector uses weather and climate services?
12. Is there a request for new products?
    a. If yes, list them and provide constraints to generate them.
    b. If not, have you identified potentially useful products for the energy sector?

Type of weather and climate services produced

13. What types of weather and climate services does your institution provide to the energy sector?
14. Are the products designed for daily, sub-seasonal, seasonal or annual timescales?
15. Do your products include climate projections?
16. Does your institution provide day-to-day information/forecast to the energy sector? What is the frequency at which the information is provided (daily, weekly, monthly, etc.), and in what form is it delivered?
17. Does your institution provide services on climate extremes (heat waves, strong winds, rainfall, floods, etc.)?

18. What is the frequency of delivery of the climate extremes products?
19. In what form does your institution provide such products: bulletin, map, etc.?
20. Are your products useful/appropriate for energy users?
21. To what extent is the climate information tailored for the energy sector?
22. Could you pick a number on a scale of 0 to 10 for the tailoring?
23. Do you have any project of improving the services being provided?
24. Does your institution often verify whether it meets the needs of the energy sector?
25. What and how is the verification method applied, if any?

EWSs

26. Does your institution provide a multi-hazard EWS to the energy sector?
27. What type of EWS is provided?
28. In what form is the information provided: map, bulletin, online platform, etc?
29. Does your institution receive feedback about the EWS from the energy sector?
30. Which of the EWS is the energy sector likely to be more interested in?
31. Are there mechanisms to support the coordination of EWS delivery?
32. Do you provide seasonal outlooks of hazard probabilities?
33. What climatic hazards are most frequent in Senegal, and which affect energy most?
34. Are all services provided on demand, or is there a policy governing provision?

Legislation/Policy/Plan

35. Is there national legislation or a mandate organizing the delivery of weather and climate services?
36. Is there a national strategy/policy for weather and climate services?
    a. If yes, does it have clear goals and responsibilities?
    b. If not, is there an ongoing procedure to set up this strategy and policy?
37. Are roles and responsibilities for the generation and dissemination of weather and climate services clearly outlined?
38. Is there a process for integrating weather and climate services into energy sector policies?
39. Is there a national action plan for weather and climate services?
40. What is the current state of the national action plan?

Questionnaire for the energy sector

Introduction

Same as ANACIM, with the following additional question

5. What is the capacity of your power plant, and in which year did it start operation?

Type of weather and climate services received

6. What type of weather and climate services does your institution receive?

7. What institution provides these services?

8. Does your institution receive information on temperature, precipitation, wind variability, etc.? And does it impact your production?

9. Do you receive information on climate extremes: flooding, heat waves, strong wind etc.

10. Does your institution receive services on climate projections?

11. Does your institution receive day-to-day forecasts from its climate information provider?

12. Do you receive services upon request, or is there a formal policy?

13. How often do you receive these services (daily, monthly, annual, etc.) and in what format (newsletter, card, etc.)? Through what channels?

14. How does your institution use climate information?

15. Are the weather and climate services tailored to your needs?

16. How does your institution assess those services?

17. List other weather and climate services you need but are not currently provided.

18. How often do you need these additional services?

19. How would the additional products be used?

20. Does your institution record climate extremes (strong wind and rainfall, heat waves, etc.?

21. How does your institution adapt to extremes?

22. Is your institution resilient to climate extremes?

23. Considering that extremes may increase in the future, is your institution prepared?

24. Is there a plan to strengthen resilience?

25. According to you, what is needed for a more resilient energy sector?

Communication framework

26. How is the communication framework with your climate information provider?

27. Does the existing framework enable regular interaction? Is it appropriate?

28. How does your institution access weather and climate services (online platform, bulletin, courier, etc.)?

29. Are they appropriate?

30. Do you need improvements?

31. Do you provide feedback to your climate information provider?

EWSs

32. Do you receive a multi-hazard EWS?

33. What type of EWS is provided?

34. In what form is information delivered?

35. Are you satisfied with EWS? Do you need improvements?

36. What type of EWS does your institution need?

37. What EWS are you more interested in?

38. Are there mechanisms to support the coordination of EWS delivery?

Legislation/Policy/Plan

Same as ANACIM.

Data availability

The authors do not have permission to share data.

References

Antwi-Agyei, P., Dougill, A.J., Doku-Marfo, J., Abaidoo, R.C., 2021. Understanding climate services for enhancing resilient agricultural systems in Anglophone West Africa: the case of Ghana. Clim. Serv. 22. https://doi.org/10.1016/j.cliser.2021.100218.

Banos de Ghisasola, E. Mapping of Climate Services Providers in Italy – Summary Report. Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), 2014. Research Paper Issue RP0213.

Bayala, J., Zougmore, R., Dayamba, S.D., Olivier, A., 2017. Climate-Smart Agriculture Technologies in West Africa: learning from ground research for development experiences. Agric. Food Secur. 6, 40.

Bazeley, P., Jackson, K., 2014. In: Qualitative data analysis with NVIVO, 2nd ed. SAGE, Los Angeles. https://doi.org/10.1080/02607476.2013.866724.

Bruno Soares, M., Dessai, S., 2016. Barriers and enablers to the use of seasonal climate forecasts amongst organisations in Europe. Climatic Change 137 (1–2), 89–103. https://doi.org/10.1007/s10584-016-1671-8.

Braun, V., Clarke, V., 2006. Using thematic analysis in psychology. Qualitative Research in Psychology 3 (2), 77–101. https://doi.org/10.1191/1478088706qp063oa.

Bruno Soares, M., Alexander, M., Dessai, S., 2018. Sectoral use of climate information in Europe: A synoptic overview. Climate Services 9, 5–20. https://doi.org/10.1016/j.cliser.2017.06.001.

Chandra, Y., Shang, L. (2019). Inductive Coding. In: Qualitative Research Using R: A Systematic Approach. Springer, Singapore. https://doi.org/10.1007/978-981-13-3170-1_8.
Christel, I., Hemment, D., Bojovic, D., Cucchietti, F., Calvo, L., Stefaner, M., Buontempo, C., 2018. Introducing design in the development of effective climate services. Clim. Serv. 9, 111–121. https://doi.org/10.1016/j.cliser.2017.06.002.
Ciscar, J.C., Dowling, P., 2014. Integrated assessment of climate impacts and adaptation in the energy sector. Energy Econ. 46, 531–538. https://doi.org/10.1016/j.eneco.2014.07.003.
Clifford, K.R., Travis, W.R., Nordgren, L.T., 2020. A climate knowledges approach to climate services. Clim. Serv. 18. https://doi.org/10.1016/j.cliser.2020.100155.
Climate change *2014: synthesis report: longer report*. (2015). [Intergovernmental Panel on Climate Change (IPCC)].
Cortekar, J., Themessl, M., Lamich, K., 2020. Systematic analysis of EU-based climate service providers. Clim. Serv. 17. https://doi.org/10.1016/j.cliser.2019.100125.
Daly, M., Dilling, L., 2019. The politics of "usable" knowledge: examining the development of climate services in Tanzania. Clim. Change 157 (1), 61–80. https://doi.org/10.1007/s10584-019-02510-w.
Danso, D.K., Anquetin, S., Diedhiou, A., Lavaysse, C., Hingray, B., Raynaud, D., Kobea, A. T., 2022. A CMIP6 assessment of the potential climate change impacts on solar photovoltaic energy and its atmospheric drivers in West Africa. Environ. Res. Lett. 17 (4). https://doi.org/10.1088/1748-9326/ac5a67.
Dayamba, D.S., Ky-Dembele, C., Bayala, J., Dorward, P., Clarkson, G., Sanogo, D., Diop Mamadou, L., Traoré, I., Diakité, A., Nenkam, A., Binam, J.N., Ouedraogo, M., Zougmore, R., 2018. Assessment of the use of Participatory Integrated climate Services for Agriculture (PICSA) approach by farmers to manage climate risk in Mali and Senegal. Clim. Serv. 12, 27–35. https://doi.org/10.1016/j.cliser.2018.07.003.
Dessai, S., Bruno Soares, M., 2015. Report Summarising Users' Needs for Seasonal to Decadal Climate Predictions. European Provision of Regional Impact Assessment on a Seasonal-to-decadal timescaleDeliverable D12.3. Leeds University. Accessible at: http://www.euporias.eu/system/files/D12.3_Final.pdf.
Dinku, T., Faniriantsoa, R., Islam, S., Nsengiyumva, G., Grossi, A., 2022. The climate Data Tool: Enhancing climate Services across Africa. Front. Clim. 3. https://doi.org/10.3389/fclim.2021.787519.
Dubus, L., Muralidharan, S., Troccoli, A., 2018. What does the energy industry require from meteorology? In Weather and climate Services for the Energy Industry. Springer International Publishing, pp. 41–63.
Fant, C., Adam Schlosser, C., Strzepek, K., 2016. The impact of climate change on wind and solar resources in southern Africa. Appl. Energy 161, 556–564. https://doi.org/10.1016/j.apenergy.2015.03.042.
Findlater, K., Webber, S., Kandlikar, M., Donner, S., 2021. Climate services promise better decisions but mainly focus on better data. Nat. Clim. Chang. 11 (9), 731–737. https://doi.org/10.1038/s41558-021-01125-3.
Hansen, J. W., Vaughan, C., Kagabo, D. M., Dinku, T., Carr, E. R., Körner, J., & Zougmoré, R. B. (2019). Climate Services Can Support African Farmers' Context-Specific Adaptation Needs at Scale. In Frontiers in Sustainable Food Systems (Vol. 3). Frontiers Media S.A. https://doi.org/10.3389/fsufs.2019.00021.
Goddard, L., 2016. From science to service: Climate services are crucial for successful adaptation to current and future climate conditions. Science 353 (6306), 1366–1367. https://doi.org/10.1126/science.aag3087.
Gunasekera, D., 2018. Bridging the Energy and Meteorology Information Gap. In: Troccoli, A. (Ed.), Weather & Climate Services for the Energy Industry. Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-319-68418-5_1.
Hewitt, C., Mason, S., Walland, D., 2012. The global framework for climate services. Nature Clim. Change 2, 831–832. https://doi.org/10.1038/nclimate1745.
Huber, I., Bugliaro, L., Ponater, M., Garny, H., Emde, C., Mayer, B., 2016. Do climate models project changes in solar resources? Sol. Energy 129, 65–84. https://doi.org/10.1016/j.solener.2015.12.016.
Lamptey, B., SAHABI ABED, S., Gudoshava, M., Mutemi, J., Bopape, M. J., Adefisan, E. A., Igri, M. P., Seidou Sanda, I., Ndiaye, O., Parker, D. J., Dougill, A. J., Fink, A. H., Knippertz, P., Woolnough, S., & Kolstad, E. W. (2024). Challenges and ways forward for sustainable weather and climate services in Africa. In *Nature Communications* (Vol. 15, Number 1). Nature Research. https://doi.org/10.1038/s41467-024-46742-6.
Larosa, F., Mysiak, J., 2020. Business models for climate services: an analysis. Clim. Serv. 17. https://doi.org/10.1016/j.cliser.2019.100111.
Mabe, F.N., Nketiah, P., Darko, D., 2014. Farmers' willingness to pay for weather forecast information in the Savelugu Nanton municipality of the Northern region. RJOAS 12 (36), 34–44.
Maguire, M., & Delahunt, B. (2017). *Doing a Thematic Analysis: A Practical, Step-by-Step Guide for Learning and Teaching Scholars.* * (Number 3). http://ojs.aishe.org/index.php/aishe-j/article/view/335.
Máñez, M., Zölch, T., Cortekar, J., 2014. Mapping of Climate Service Providers. Theoretical Foundation and Empirical Results: A German Case Study CSC Report 15. Climate Service Center, Germany.
Mashuri, S., Sarib, M., Rasak, A., Alhabsyi, F., 2022. *Semi-structured Interview: A Methodological Reflection on the Development of a Qualitative Research Instrument in Educational Studies*. Ruslin 12 (1), 22–29. https://doi.org/10.9790/7388-1201052229.
Meque, A., Gamedze, S., Moitlhobogi, T., Booneeady, P., Samuel, S., Mpalang, L., 2021. Numerical weather prediction and climate modelling: challenges and opportunities for improving climate services delivery in Southern Africa. Clim. Serv. 23. https://doi.org/10.1016/j.cliser.2021.100243.
Mideksa, T.K., Kallbekken, S., 2010. The impact of climate change on the electricity market: a review. Energy Policy 38 (7), 3579–3585. https://doi.org/10.1016/j.enpol.2010.02.035.
Müller, J., Folini, D., Wild, M., Pfenninger, S., 2019. CMIP-5 models project photovoltaics are a no-regrets investment in Europe irrespective of climate change. Energy 171, 135–148. https://doi.org/10.1016/j.energy.2018.12.139.
Naab, F.Z., Abubakari, Z., Ahmed, A., 2019. The role of climate services in agricultural productivity in Ghana: the perspectives of farmers and institutions. Clim. Services 13, 24–32. https://doi.org/10.1016/j.cliser.2019.01.007.
Ndiaye, A., Moussa, M.S., Dione, C., Sawadogo, W., Bliefernicht, J., Dungall, L., Kunstmann, H., 2022. Projected changes in Solar PV and Wind Energy potential over West Africa: an Analysis of CORDEX-CORE Simulations. Energies 15 (24). https://doi.org/10.3390/en15249602.
Ogunjobi, K.O, V.O, A., A.H, F., & O.W, I. (2022). Projected changes in wind energy potential using CORDEX ensemble simulation over West Africa. *Meteorology and Atmospheric Physics*, *134*(3). https://doi.org/10.1007/s00703-022-00880-y.
Roudier, P., Sultan, B., Quirion, P., Baron, C., Alhassane, A., Traore, S.B., Mullere, B., 2012. An ex ante evaluation of the use of seasonal climate forecasts for millet growers in SW Niger. Int. J. Climatol. 32, 759–771.
Sawadogo, W., Reboita, M.S., Faye, A., da Rocha, R.P., Odoulami, R.C., Olusegun, C.F., Adeniyi, M.O., Abiodun, B.J., Sylla, M.B., Diallo, I., Coppola, E., Giorgi, F., 2021. Current and future potential of solar and wind energy over Africa using the RegCM4 CORDEX-CORE ensemble. Clim. Dyn. 57 (5–6), 1647–1672. https://doi.org/10.1007/s00382-020-05377-1.
Schaeffer, R., Szklo, A. S., Pereira de Lucena, A. F., Moreira Cesar Borba, B. S., Pupo Nogueira, L. P., Fleming, F. P., Troccoli, A., Harrison, M., & Boulahya, M. S. (2012). Energy sector vulnerability to climate change: A review. In *Energy* (Vol. 38, Issue 1, pp. 1–12). Elsevier Ltd. https://doi.org/10.1016/j.energy.2011.11.056.
Steynor, A., Pasquini, L., 2022. Using a climate Change Risk Perceptions Framing to Identify Gaps in climate Services. Front. Clim. 4. https://doi.org/10.3389/fclim.2022.782012.
Sultan, B., Lejeune, Q., Menke, I., Maskell, G., Lee, K., Noblet, M., Sy, I., Roudier, P., 2020. Current needs for climate services in West Africa: results from two stakeholder surveys. Clim. Serv. 18. https://doi.org/10.1016/j.cliser.2020.100166.
Tall, A., Coulibaly, J. Y., & Diop, M. (2018). Do climate services make a difference? A review of evaluation methodologies and practices to assess the value of climate information services for farmers: Implications for Africa. In Climate Services (Vol. 11, pp. 1–12). Elsevier B.V. https://doi.org/10.1016/j.cliser.2018.06.001.
Tart, S., Groth, M., Seipold, P., 2020. Market demand for climate services: an assessment of users' needs. Clim. Serv. 17. https://doi.org/10.1016/j.cliser.2019.100109.
Troccoli, A., Goodess, C., Jones, P., Penny, L., Dorling, S., Harpham, C., Dubus, L., Parey, S., Claudel, S., Khong, D.-H., Bett, P.E., Thornton, H., Ranchin, T., Wald, L., Saint-Drenan, Y.-M., de Felice, M., Brayshaw, D., Suckling, E., Percy, B., Blower, J., 2018. Creating a proof-of-concept climate service to assess future renewable energy mixes in Europe: an overview of the C3S ECEM project. Adv. Sci. Res. 15, 191–205. https://doi.org/10.5194/asr-15-191-2018.
Turnpenny, J., Haxeltine, A., O'Riordan, T., 2004. A scoping study of user needs for integrated assessment of climate change in the UK context: Part 1 of the development of an interactive integrated assessment process. Integr. Assess. 4 (4), 283–300.
Vaughan, C., Dessai, S., 2014. Climate services for society: Origins, institutional arrangements, and design elements for an evaluation framework. Wiley Interdiscip. Rev. Clim. Chang. 5 (5), 587–603. https://doi.org/10.1002/wcc.290.
Vaughan, C., Dessai, S., Hewitt, C., Baethgen, W., Terra, R., Berterretche, M., 2017. Creating an enabling environment for investment in climate services: the case of Uruguay's National Agricultural Information System. Clim. Serv. 8, 62–71. https://doi.org/10.1016/j.cliser.2017.11.001.
Vincent, K., Daly, M., Scannell, C., Leathes, B., 2018. What can climate services learn from theory and practice of co-production? Climate Services 12, 48–58. https://doi.org/10.1016/j.cliser.2018.11.001.
Vogel, C., Steynor, A., & Manyuchi, A. (2019). Climate services in Africa: Re-imagining an inclusive, robust, and sustainable service. In *Climate Services* (Vol. 15). Elsevier B. V. https://doi.org/10.1016/j.cliser.2019.100107.
WMO, 2014: Implementation Plan of the Global Framework for Climate Services, p. 2, Box 1. http://www.wmo.int/gfcs/sites/default/files/implementation-plan//GFCSIMPLEMENTATION-PLAN-FINAL-14211_en.pdf.
WMO_Climate_services_Energy_en. (2022): State of Climate Services Energy.
Zongo, B., Diarra, A., Barbier, B., Zorom, M., Yacouba, H., Dogot, T., 2014. Farmers' perceptions and willingness to pay for climate information in Burkina Faso. J. Agric. Sci. 8 (1), 175–187.