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by

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TOPIC: Climate change impact on the energy sector and sustainable supply in line with the Malian National Determined Contribution (NDCs).

Thesis defence: On ……February 2025 at ….:00 AM in Niamey, Niger

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- Abstract

The sustainability of countries' energy systems requires long-term energy planning. Energy is key to the sustainable development of the modern world and indispensable to maintaining long-term energy planning. Energy systems are greatly affected by climate change, which is projected to alter countries and cities' energy demand and supply systems. Global warming is projected to affect energy systems. Greenhouse gases (GHGs) effect increasing is already changing the world's climate, increasing atmospheric temperatures, and affecting the land surface, with precipitation patterns changing at the same time as the energy systems. Long-term energy systems and adapted policies to fight against climate change are required.

This thesis focuses on long-term energy planning in the context of the changing climate and the various energy policies put in place to adapt and mitigate climate change. The thesis presents an extensive and in-depth analysis of the country's energy systems in response to longer-term energy supply sustainability. It looks at the general context of energy systems (supply and generation); moreover, it looks at the sustainability of the current and future energy supply and projects the impact of climate change on different climate energy parameters (precipitation, wind, short wave radiation, sunshine duration, etc.) that affect energy generation. Afterward, the Regional Climate Models (RCMs) are used to project the mid- and long-term climate change impact on the Malian energy system. This research assesses the impacts of climate change on energy systems using the climate projections from CORDEX GCMs driven by RCPs 4.5 and 8.5. The RCP 4.5 scenario represents a more moderate pathway of greenhouse gas emissions, while the RCP 8.5 scenario represents a high-emission future. These scenarios provide a range of possible climate futures for Mali. The results of the study indicate that under both selected scenarios, there will be significant variation in the analysed climate-energy parameters, causing the instability of renewable energy production systems, hence the instability of energy systems and the country's energy supply. The findings show a decrease in precipitation, which could impact hydropower generation. Additionally, there will be a decrease in wind speeds, potentially affecting wind energy production. Furthermore, there will be an increase in temperature, leading to higher cooling demand and increased strain on the energy system. Overall, the findings show how crucial it is to structure the energy system and energy policies in order to sustainably transition to renewable energy sources and effectively minimise the effects of climate change on energy production in Mali.

Résumé

La durabilité des systèmes énergétiques des pays nécessite une planification énergétique à long terme. L’énergie est la clé du développement durable du monde moderne et indispensable au maintien d’une planification énergétique à long terme. Les systèmes énergétiques sont fortement affectés par le changement climatique, qui devrait modifier le demande et l’approvisionnement énergétiques des pays et des villes. Le réchauffement climatique devrait affecter les systèmes énergétiques. L’effet de l’augmentation des gaz à effet de serre (GES) modifie déjà le climat mondial, augmentions des températures atmosphériques et affecte la surface terrestre, les régimes de précipitations changeant en même temps que les systèmes énergétiques. Des systèmes énergétiques et des politiques à long terme de lutte contre le changement climatique sont nécessaires. Cette thèse se concentre sur la planification énergétique à long terme dans le contexte du changement climatique et les différentes politiques énergétiques mises en place pour adapter et atténuer le changement climatique. La thèse présente une analyse approfondie et approfondie des systèmes énergétiques du pays en réponse à la durabilité de l’approvisionnement énergétique à long terme. L’étude examine le contexte général des systèmes énergétiques (approvisionnement et production) ; en outre, il examine la durabilité de l’approvisionnement énergétique actuel et futur et projette l’impact du changement climatique sur différents paramètres énergétiques climatiques (précipitations, vent, rayonnement à ondes courtes, durée d’ensoleillement, etc.) qui affectent la production d’énergie. Ensuite, les modèles climatiques régionaux (GCMs) sont utilisés pour projeter l’impact du changement climatique à moyen et long terme sur le système énergétique malien.

Cette étude évalue les impacts du changement climatique sur les systèmes énergétiques à l’aide des projections climatiques des CORDEX pilotées par les RCP 4.5 et 8.5. Le scénario RCP 4.5 représente une évolution plus modérée des émissions de gaz à effet de serre, tandis que le scénario RCP 8.5 représente un avenir à émissions élevées. Ces scénarios offrent une gamme d’avenirs climatiques possibles pour le Mali. Les résultats de l’étude indiquent que dans les deux scénarios sélectionnés, il y aura une variation significative des paramètres climat-énergie analysés, provoquant l’instabilité des systèmes d’énergies renouvelables, d’où l’instabilité des systèmes énergétiques et de l’approvisionnement énergétique du pays. Les résultats montrent une diminution des précipitations, ce qui pourrait avoir un impact sur la production hydroélectrique. De plus, la vitesse du vent diminuera, ce qui pourrait affecter la production d’énergie éolienne. En

outre, la température augmentera, ce qui entraînera une demande de refroidissement plus élevée et une pression accrue sur le système énergétique. Dans l’ensemble, les résultats montrent à quel point il est crucial de structurer le système énergétique et les politiques énergétiques afin d’assurer une transition durable vers les sources d’énergie renouvelables et de minimiser efficacement les effets du changement climatique sur la production d’énergie au Mali.

Dedication

To my parents **Adama Doumbia** and **Bintou Coulibaly** for their Sacrifices, love, and support, and my profound gratitude to them for their help and their guidance.

To my husband for his love, support, and patience, and to my daughter behind my motivation through this Journey.

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Declaration

I, Safiatou Mariko, hereby declare that this thesis represents my personal work, to the best of my knowledge the thesis work is free of any kind of plagiarism. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

Signed:

Name: Safiatou Mariko **Date:** _____/____/2025

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List of acronyms

GHGs	Greenhouse gases
RCMs	Regional Climate Models
GCMs	Global Climate Models
RCP	Representative concentration projects
NDCs	Nationally Determined Contributions
MCDM	Multi-criteria decision making
ESGF	Earth System Grid Federation
WPD	Wind Power Density
EDM	Energie du Mali
WAPP	West African Power Pool
GTDV	Generation-Transmission-Distribution-Sale
PTDS	Purchase-Transmission-Distribution-Sale
SHS	Solar home systems
RES	Renewable energy services
LPG	Liquified petroleum gas
NAPA	National Adaptation Programme of Action
NCCS	National Climate Change Strategy
CMIP5	The Coupled Model Intercomparison Project Phase 5
MCA	Multi-criteria analysis and assessment
CBA	Cost-benefit analyses
LCA	Life cycle analysis
WSM	Weighted sum method
WPM	Weighted product method
AHP	Analytic hierarchy process;
MULTIMOORA	Multi-objective optimization by ratio analysis
ATEP	Total Primary Energy Supply
BAU	Business as usual
ELECTRE	Elimination et choice translating reality
GHG	Greenhouse gases
GTDV	Generation-Transmission-Distribution-Sale
MCDM	Multi-criteria decision making
NDCs	Nationally Determined Contributions

PANEE	Plan d ’action d’efficacité énergétique
PANER	Plan d’action d'énergie renouvelable
PEN	National Energy Policy
PROMETHE	Preference ranking organization method for enrichment evaluation
RCPs	Representative Concentration Pathway
RES	Renewable energy services
TOPSIS	Technique for order preference by similarity to ideal solution
WPD	Wind power density
WPM	Weighted product method
WSM	Weighted sum method

List of Symbols

γ : constant
ρ: air density (kg/m3)

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Chapter I: Introduction

I.1. General Introduction

Besides recent rapid economic and population growth (3% growth rate) of 19.6 million inhabitants in 2018, energy access rate remains very low in Mali. According to the national directory of energy, electricity demand is growing at a rate of about 10% per year *(DNE., 2021).* Fuel demand for transport is increasing at an even higher rate *(BAD., 2010; Nygaard et al., 2012*). Additionally global warming is altering countries and cities' energy demand and supply systems *(Wang et al., 2020).* The Malian energy generation system is primarily based on natural resources such as biomass (used in the form of fuel wood for cooking and heating), hydroelectricity, and petroleum products for power generation and transport. Irregularities and variabilities in precipitation (level and intensity), rising air temperatures, etc are factors that can severely impact the energy production and energy supply of the country. Climate change and other environmental problems represent enormous challenges in achieving energy sustainability and providing sufficient energy for all at a reasonable price. Promoting access to clean, affordable, and sustainable energy in the country (rural and urban areas included) according to the UN's Sustainable Development Goal 7 and the African Union Agenda 2063 aspirations, particularly in the Malian context will require meeting several challenges among which: the growing demand, diversifying energy production resources, developing and implementing new energy production technologies, etc. Achieving the environmental and climate target of 31% *(CPDN., 2016)* of greenhouse gas emission reduction from the energy sector (the country's objectives for the Paris Agreement under the Nationally Determined Contribution) will necessitate efficient energy systems capable of improving energy access, reducing pollutant emissions, and lowering the country's dependence on fossil fuel imports while meeting the energy demand and improving the energy supply and economic needs of the country without reducing energy quality as well as decarbonizing the energy sector (renewable energy technologies) at the same time. Hence, this work would take a look at the Malian energy sector (energy resources and energy use, imports, supply demand) and evaluate the current energy state (production and consumption) to identify opportunities to cut down greenhouse gas emissions, transition opportunity, drivers and barriers for a more clean and sustainable energy supply in the mid- and long-term in order to improve energy access and increase local energy penetration (expansion). Sustainable energy planning plays a critical role towards achieving country's engagement to climate goals stated in the national determined contributions and proper natural resources management. Furthermore, long-term energy sustainability and the country's energy transition will be investigated to determine the extent to which renewable energy resources would be impacted by climate change.

To achieve this, the present work will consider earlier research, conference releases, and national communications about the country's energy situation. Data gathered during surveys conducted with the various energy agencies and sector actors was used for additional insight into the energy sector in Mali.

I.2. Context

Energy supply is critical to countries' societal and economic *development (SE4ALL., 2019).* It is needed to maintain a pleasant climate in homes and offices, feed manufacturing industries, transport, everyday cooking, heating and lighting activities, etc. Rapid urbanisation and a quick demographic increase are the main drivers of the energy demand (Climate4Impact). The rising demand could result in several issues, including unstable energy supplies, unsustainable production, and heavy reliance on fossil fuels *(Zolfani and Saparauskas., 2013)*, ultimately leading to climate change. The need for space conditioning, particularly residential cooling, is expected to increase due to climate change, which will also change the energy systems (power production and consumption) by decreasing the efficiency of thermal conversions and renewable energy generation (renewable energy driven by weather patterns*) (Wang et al., 2020).* It necessary to significantly increase the proportion of total global energy generation and consumption from renewable energy sources to combat (adaptation and mitigation) the changing climate *(Raghuvanshi et al., 2008).* Renewable energy sources: wind, solar, and biomass are undoubtedly impacted by weather variabilities, and the environment in various ways. High temperatures, Climate change (and shift of other climate variables) have an impact energy system particularly renewable energy (consumption, production and supply) sources (solar energy, wind energy, and biomass) *(Ministerrådet., 2012).*

The energy sector is the largest source of greenhouse gas emissions; to fulfil the country Nationally Determined Contributions (NDCs) transitioning from a fossil fuel-dominated system to a renewable-driven energy system is seen as an alternative to be considered. Renewable energy sources are crucial to the decarbonization strategies, and to limit the harmful effects of climate change *(Zhao et al., 2020),* particularly in Sahelian countries like Mali, increasing focus should be placed on studying the sensitivity of the energy system to climate change and its variabilities *(Thrid National Communication Mali., 2018).*

Reduced availability of renewable energy resources, would decrease the capacity production from these sources, impede the delivery of sustainable, affordable, clean, and secure energy supply by countries, additionally impede their capabilities of implementation of the Paris Agreement's *(Emodi et al., 2019; Zhao et al., 2020)*. Hence to avoid energy system disruptions, lower energy costs, and better inform policy decision makers, it is important to understand the nature of these changes.

I.3. Observations

Mali is ranked 181 out of 188 countries considering the per capita GHG emissions; hence, it is considered a carbon sink *(Warner., 2018)*. The country signed the Paris Agreement for Climate Change in April 2016 and ratified it in September 2016, nationally determined contribution plans to reduce emissions in key sectors: 31% for energy, 29% for agriculture, and 21% for land use change and forestry *(CPDN., 2016)* compared to its baseline scenarios that predict an annual emission increase of 6.9% between 2015 and 2030 *(African Development Bank Group & Green Mini-grid Market Development., 2018)*. Energy consumption in the residential sector of Mali relies on biomass for about 96% of final consumption and is responsible for 83% of the total emissions of the energy sector. The sector's emissions are expected to grow with rapid population growth and climate change. This will increase the need for space conditioning and the need for electricity. The main greenhouse gas emissions in the Malian energy sector are located in the following sectors: The production of primary energy (wood), secondary energies (electricity, charcoal), corresponding to the transformation of secondary energies (gas oil, DDO, fuel) and electricity and (wood) into charcoal for primary energy; Consumption of primary (wood, primary electricity) and secondary energy (electricity, petroleum products, charcoal) *(TCN., 2018)*.

According to the Malian Third National Communications, a significant share of greenhouse gas (GHG) emissions is identified in energy sector. Between 2007 and 2014, GHG emissions from energy production and consumption registered have shown an average annual increase of 6.44%. The emissions were from the residential sub-sector, the transport sub-sector, and the processing sub-sector particularly for fuel consumption from electricity production *(Third National Communication Mali, 2018)*. This is an indication that mitigation and adaptation policies must be oriented towards the energy sector.

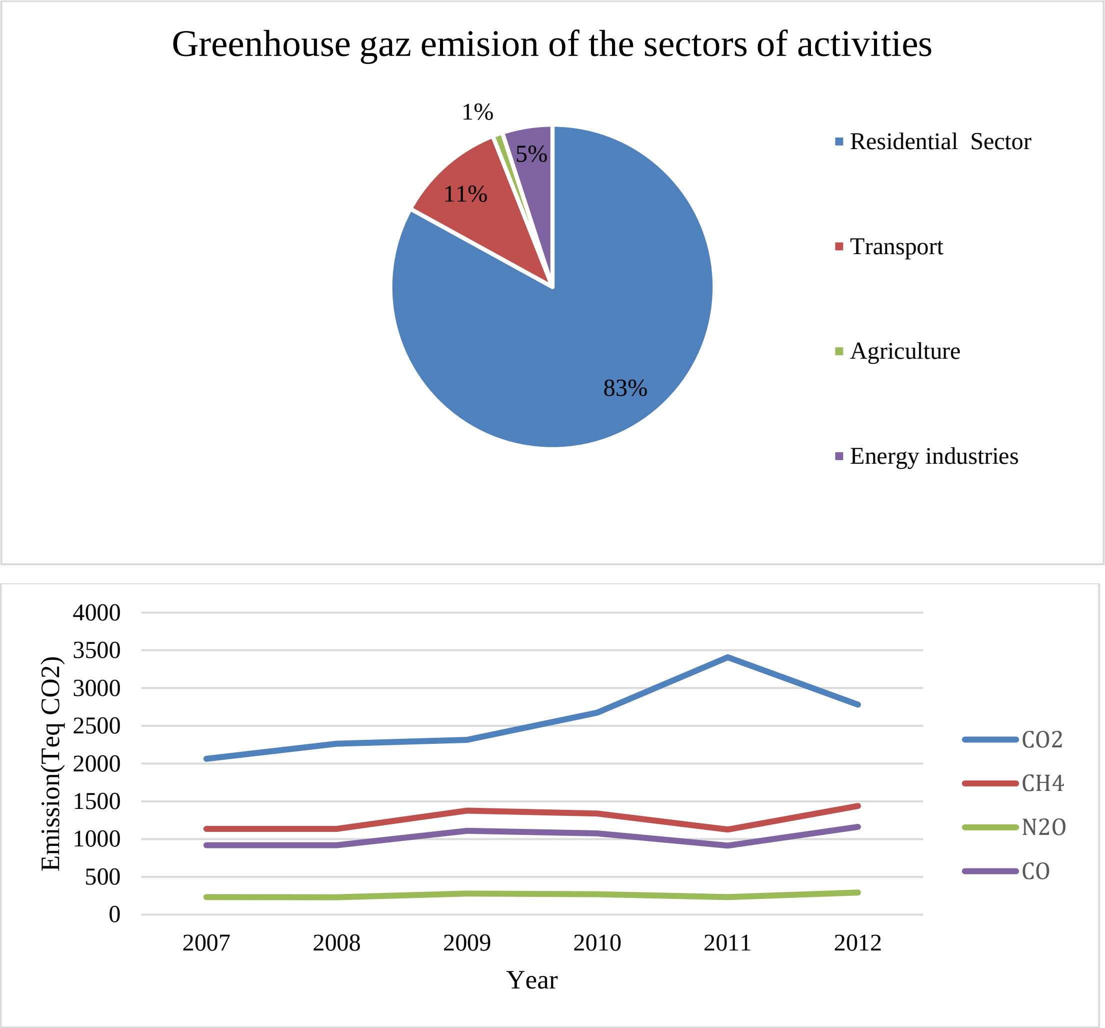


Figure 1: Greenhouse Gas Emission in Mali (in the energy sector) (Durable., 2017)

In Mali, 60% of electricity demand is met by hydroelectricity, which is dependent on rainfall *(Fronteras., 2016; AfDB., 2015)*. Hence the Malian energy sector's dependency on hydropower and biomass, therefore, the country energy system is highly vulnerable to climate change and variabilities (*AfDB., 2015; PANEE., 2015; PANER., 2020)*. The impact of climate change must be considered to ensure a secure energy supply over the long term *(IRENA., 2019)*. Possible adaptation measures for both demand (promotion of energy efficiency) and supply (promotion of less vulnerable sources, such as solar energy or even hybrid systems to compensate for variability) are to be considered.

I.4. Problem statement

The current Malian primary energy supply is largely based on biomass (78%) which puts a lot of pressure on forests (a strong driver for deforestation). Electricity generation is also dominated by hydroelectricity, representing 60% of the production in 2012 from Manantali and Sélingué dams *(AfDB., 2015)*. Oil and gas sub-sector generate more than 20% of the electricity in the country, translating the total dependence on imports, which exposes the economy to the volatility of fossil fuel prices. In 2013, thermal electricity generation represented 47% of electricity produced in Mali, and other and still no significant representation of renewable energy in the electricity generation mix *(AfDB., 2015).* Heavy dependence on biomass, hydropower, energy import, power shortage, increasing GHG emissions, the great vulnerability of renewable energy resources to climate variability and change are the key challenges faced by the Malian energy sector. Therefore, special attention is to be given to diversification, sustainability, and reliability issues of the country's energy supply.

The development of renewable energy can reduce energy imports, contribute to the diversification of supply options, reduce economic vulnerability to fossil fuel price's volatility, and represent opportunities to enhance energy security *(Owusu and Sarkodie., 2016).* Mali has significantly untapped renewable energy potentials (solar, wind, and hydro). The monthly solar average values observed vary from 5 to 7 kWh/m^2 /day, for an insolation duration of 8 to 10 hours/day *(Diarra., 2017).* The average wind speed is also relatively important between 3 and 7 m/s. In the northern part of the country, the average annual wind speed is about 5 to 7 m / s against less than 4m / s in the centre and the southern part *(Fronteras., 201*6). River Niger is an important hydropower resource for the country and several others in the region (*Diarra., 2017*; *Third National Communication Mali, 2018; Fronteras., 2016).*

The Decreased rainfall, higher temperatures, and higher variability in rainfall patterns are set to reduce hydroelectricity production (potential and production) by up to 22% by 2025 and decrease fuel wood production *(Zamudio., 2016).*

Hence the present study proposes to look at the links between climate change and sustainable energy supply in Mali. Current studies focused on mapping renewable energy resources potentials of the country *(Nygaard et al., 2017, Nygaard et al., 2012, Nygaard et al., 2010)* very few have looked at the impact of long-term climate change on the energy supply sustainability.

West African countries like many other Sub-Saharan African countries depend exceedingly on biomass for domestic cooking and heating purposes. In these countries the energy generation mix is weakly diversified; 160 million grid-connected electricity consumers live in countries where hydro-power accounts for over 50% of total power supply *(Falchetta et al., 2019).* Access to energy represents a key factor to consider in poverty reduction and sustainable development. In 2016, with a maximum available generating capacity of 12GW, the West Africa region had an estimated 25.6GW peak demand *(Adeoye and Spataru., 2018).* To date, the Sahel countries (Mali, Niger, Burkina Faso, etc.) have an electrification rate of about 26%, about three times lower than the world average and twice the average for sub-Saharan African countries *(Sahel alliances energy., 2019).* That reflects the regular power outages and load shedding that countries endure, as well as the existing disparity between the region's supply and demand for electricity. Solar home systems, hybrid mini grids driven by diesel and solar power, hydropower, and diesel-powered generators are the most common power generation methods in Mali.

Knowledge of climate change's impact on the energy sector can be a key contribution to achieving the UN's Sustainable Development Goals (SDG7: ensuring access to affordable, reliable, sustainable, and modern energy for all). It can also be of key importance for climate change adaptation and mitigation projects and help countries in better planning the energy transition. In the long term, it will ensure energy security and the achievement of sustainable development goals 7 and 13 and help fulfil the Paris Agreement *(Emodi et al., 2019).*

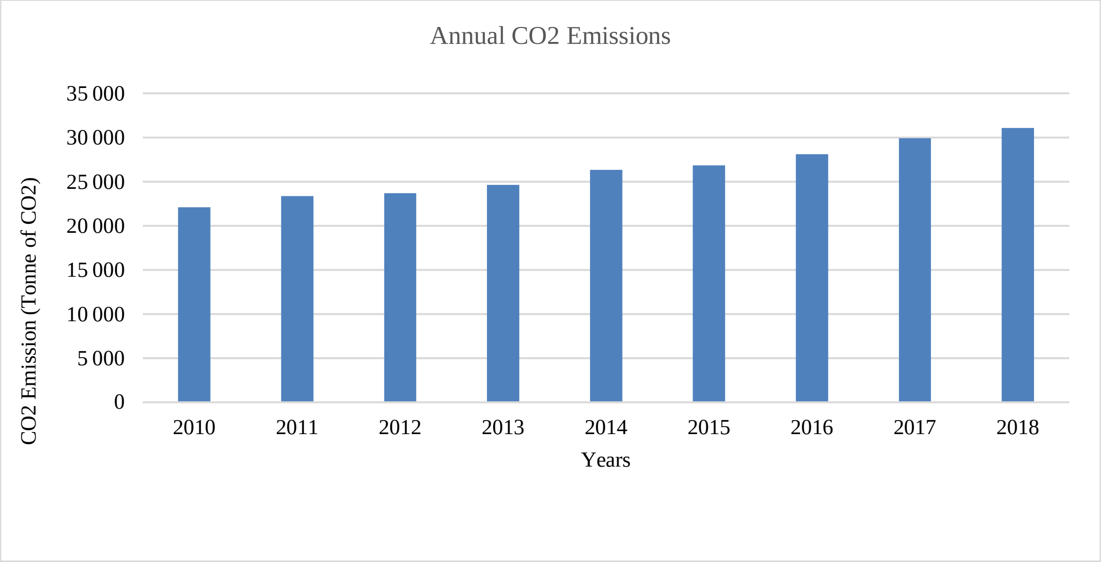


Figure 2: greenhouse gas emission in the sector of energy (Thrid National Communication Mali, 2018)

Renewable energy generation is directly linked to variations in climate variables such as precipitation, temperature, irradiation, and wind speed. The growing physical impacts of climate change are among the challenges that renewable energy resources will face. They implications for the reliability and performance of the energy system and could also hinder the energy supply *(Solaun and Cerda., 2019).*

Mali experiences several hours of power shortages per year, most occurring during the hottest months of the year from March to July when demand for electricity, space conditioning is at its highest. Availability, reliability, accessibility, and affordability, describe important features of sustainable power supply, they are also critical criteria for sustainable energy supply for all. A reliable energy supply is fundamental for energy security, and climate change mitigation and promoting the use of renewable sources has been increasingly relevant to this effect *(Senatro et al., 2020)*. Thus, this study will evaluate (estimate) climate change impacts on the Malian energy systems and propose a sustainable mix-energy supply system in line with the Malian NDCs at horizon 2100 for a clean energy transition.

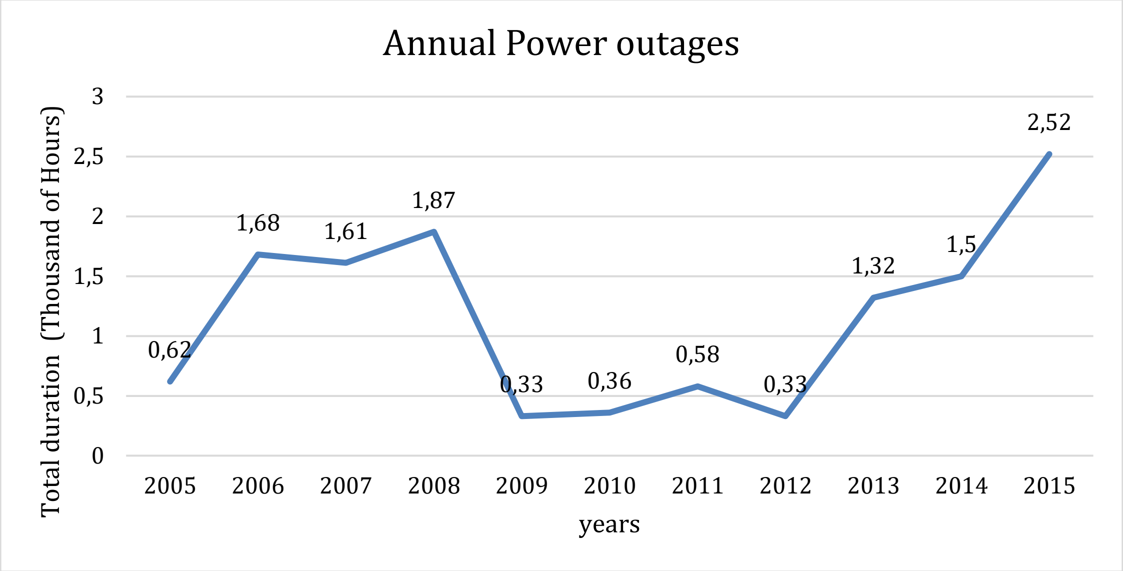


Figure 3: Total number of annual power outages (DNE., 2020)

I.5. Thesis Aim, Objectives, and Key Research Question

a. Aim

The main aim of this work is to use multi-approach methodology to assess the Malian energy system, adaptation (development) policies and strategies to design future energy systems considering energy sustainability criteria.

b. Objectives

Design an energy system for sustainable supply considering climate change and variability in line with the Malian nationally determined contributions at horizon 2100.

c. Specific Objectives:

Evaluate the country's current energy situation.

Evaluate the country's energy system sustainability under different climate scenarios.

Evaluate the impacts of climate change and variability on the energy system sustainable energy supply system in line with the NDCs.

d. Research questions

With respect to the problem stated above, the main questions that the study tries to answer are:

RQ1: How can the Malian energy system transition towards a more sustainable energy?

RQ2: How are the energy resources and energy systems affected by climate change, and to what extent?

RQ3: What is the role of renewable energy in supporting the development of a sustainable supply of energy in Mali?

e. Research hypothesis

H1: Climate change and variability negatively impact energy resources and energy systems respectively in terms of availability, energy generation, and sustainability.

H2: Reducing emissions in key sectors (agriculture, forestry, energy) in line with the NDCs through increasing renewable share in Mali will help sustainable energy transition and mitigate climate change.

H3: Increasing the energy generation through (hydro, solar, and wind) in Mali's energy system will allow a sustainable energy supply in the country.

I.6. Structure of the thesis

Chapter 1 presents the generalities of the study, the problem statement and the objectives. Chapter 2: Literature Review focuses on the various literature in this field. The chapter digs into the vast and precedent literature on energy sustainability, energy planning, and climate impact on energy systems. It reviews the impact of climate change on energy systems studies and gives particular attention to the different methodologies used. It explores the work done on the subject matter, namely: energy sustainability, multi-criteria decision making (MCDM), climate change impact on energy systems, and highlights the gaps that the study is trying to deal with. Chapter 3 is dedicated to the assessment of the Malian current energy situation. It introduces the energy sector of the country, dependencies and the challenges etc. It highlights the system's high predominance on biomass energy (used mostly for cooking) and hydropower (electricity). Chapter 4 presents the research Methodology; it explains the methods used for collecting data and explains the method of analysis behind multi-criteria decision-making (MCDM) and climate impacts assessment to project the future climate changes impact on the country's energy systems. Chapter 4 presents the results. Lastly, Chapter 5 presents the general conclusion, final recommendations and perspectives.

Chapter II: Literature Review

II.1. Introduction

Increasing efforts have been made through the years to ensure the sustainability of energy systems. It is crucial to provide policymakers, governments, and energy practitioners with a scientific understanding of the country's future energy deployment to address future energy supply sustainability questions. The scientific community has been paying greater attention to the influence of climate change on energy supply sustainability to advise decision- makers about anticipated future changes to the energy systems for the development of countries' energy systems. The following will take a close look at some recent scientific contributions concerning this topic. The topics of energy sustainability, energy planning, and climate change's impact on energy, as well as sustainability are also discussed. The study will examine various research studies and reports that explored the relationship between energy sustainability and climate change; identify knowledge gaps considering the field and provide valuable insights into the challenges and opportunities that may help the country transition towards a more sustainable energy system.

II.2. Sustainability assessment of the energy systems

The current policies to adapt and mitigate the effects of climate change recommend shifting from the use of fossil fuels to renewable energy technologies, which are highly influenced by climate variability and changes. Considering increasing energy demand and the national and international policies on energy resource production and supply (use of renewable energy and greenhouse gas emission reduction), the question of energy system sustainability of countries remains the most urgent question of the 21st century. Sustainability of energy systems requires all sustainability dimensions environmental, technical, social, and economic to be considered. The weight of each dimension has to be determined depending on the importance of the dimension considering the sustainability assessment goals. An important step in the sustainability assessment of any energy system is the definition of the sustainability indicators (*Santoyo-Castelazo and Azapagic., 2020).* Sustainability assessment is done through applying a multi-criteria decision analysis which evaluates different scenarios of a solution. Multi-criteria decision analysis is a renowned method of energy system sustainability assessment *(Mortey et al., 2017; Bhandari et al., 2019).* The multi-criteria assessment is based on the decision-making procedure reflecting the combined effect of all criteria under consideration and is expressed in the form of a general index of sustainability. The optimal scenario will be assessed considering technical, economic, environmental, and socio-political domestic and global energy circumstances know as sustainability dimension.

1. Literature review sustainability analysis of energy systems:

Over the years, sustainable energy supply systems have had many definitions by authors *(Bhardwaj et al., 2019; Carvalho., 2000; Faaij., 2006; Karger and Hennings., 2009; Kempener et al., 2015; Quinn et al., 2018; Remeikienė et al., 2021; Siksnelyte-Butkiene et al., 2020; Tolnov and Rudolph., 2020).* Energy sustainability implies the availability, affordability, applicability, and acceptability of countries' energy supply *(Turner and Peimani., 2019).* Sustainable energy systems incorporate aspects of supply security and efficiency, considering the aforementioned dimensions of energy sustainability assessment. *Kanudia et al., (2013),* energy security is a necessary component of the metrics of energy sustainability. Energy security is defined as the uninterrupted provision of vital energy services for all, designated as one of the attributes needed to achieve energy sustainability, together with availability, affordability, access, health, and climate *(Kanudia et al., 2013).* The most famous dimension for sustainability measurement is identified as the Three Pillar Model (technical, economic, and social) with economic, social, and environmental dimensions (*Bhandari et al., 2018*). The impact of energy systems (energy use, production pattern, and energy service quality) on development and the overall impact on environmental sustainability is measured using the environment dimension of energy supply. Technical sustainability is measured using the technical dimension, and the social dimension measures the availability, the energy services and contribution to the social well-being of the local community, and social development. Sustainability of energy systems must take into consideration the needs to ensure the system's capability to meet the requirements set by consumers, not only in terms of installed power and availability but also in all aspects of sustainable development *(Richardson., 2010).* Designing a sustainable energy system is a laborious procedure involving many different aspects of energy system requirements. The planning and analysis of energy systems have become more challenging due to the involvement of different actors with varying perspectives based on various aspects of sustainability. Hence the use of MCDM tools, which have the capacity to consider all these factors.

Tools for sustainability assessment can be divided into three groups: monetary, biophysical, and indicator tools *(Dombi et al., 2014).* Multi-criteria analysis and assessment (MCA) are appropriate methods of sustainability assessment. To design or plan for sustainable energy supply systems, authors have wisely applied MCMD, known as multi-criteria decision-making *(Dombi et al., 2014; Bhandari et al., 2021; Demirtas.,* *2013; Saavedra et al., 2018; Diakoulaki and Karangelis., 2007).* Cost-benefit analyses and life cycle analyses is also applied in sustainable energy systems planning. Both tools are also importantly used in sustainable energy systems planning *(Häyhä et al., 2011).*

CBA is a fundamental tool in evaluating the economic viability of sustainable energy initiatives. By quantifying the costs and benefits associated with projects, decision-makers can determine whether the investment aligns with the project's economic objectives. It considers factors such as the initial capital outlay, operational and maintenance costs, energy savings, reduced emissions, and the value of environmental and societal benefits. It helps in prioritizing projects that offer the highest net benefits, making it a crucial component of responsible decision-making in the energy sector. On the other hand, LCA takes a holistic approach by assessing the environmental impacts associated with the entire life cycle of an energy system, from raw material extraction to manufacturing, installation, operation, and decommissioning. LCA helps identify potential hotspots of environmental harm, allowing engineers and policymakers to make informed choices that minimize ecological footprints. By combining LCA with CBA, decision-makers can make decisions that not only make economic sense but also contribute to long-term environmental and social sustainability *(Whittaker et al., 2015).*

Multi-criteria decision Analysis (MCDA) is used in various contexts to evaluate and compare different options or alternatives based on multiple criteria or objectives. In the energy sector, MCDA can be particularly valuable when making complex decisions related to energy generation, distribution, and consumption. The primary objective of MCDA is to assist decision-makers in selecting the most suitable option or alternative when faced with multiple conflicting criteria or objectives regarding cost-effectiveness, environmental impact, reliability, and social acceptance of energy system.

The use of MCDM in energy system planning can be distinguished into two to three categories: the first is based on analysing and comparing individual generation technologies based on their inherent economic, social, and ecological properties; the second is based on evaluating the performance of the overall energy supply system, usually by examining different energy supply mixes for specific regions or countries (*Brand and Missaoui., 2014).* Lastly, look for a good location for a plant.

MDCM is a branch of operational research that uses analytical methods to make proper decisions (*Kumar et al., 2019).* It addresses complex problems with inconsistent objectives, heterogeneous data, interest, and uncertainty, such as those in energy planning. MCDM is used to evaluate and compare different alternatives or options. These alternatives can include different energy sources (e.g., coal, natural gas, renewable energy), energy technologies (e.g., solar panels, wind turbines, nuclear reactors), or energy policy choices (e.g., carbon pricing, subsidies). Various MCDMs are used in energy planning: weighted sum method (WSM); weighted product method (WPM); AHP (analytic hierarchy process); ELECTRE (elimination and choice translating reality), preference ranking organization method for enrichment evaluation (PROMETHE). MULTIMOORA (multi-objective optimization by ratio analysis) and TOPSIS *(Streimikiene et al., 2012).* MCDM has been widely applied to energy supply systems *(Liu., 2014; Brand and Missaoui., 2014; Al Irsyad et al., 2019; Dombi et al., 2014; Stein., 2013; Santoyo-Castelazo and Azapagic., 2014; Mortey et al., 2017). T*he choice of methodology depends on the specific decision problem, the availability of data, the preferences of decision-makers, and the nature of the criteria and alternatives involved. It's often helpful to engage with experts and stakeholders when selecting and applying MCDM methodologies to ensure that the chosen approach aligns with the decision context and objectives.

2. Description of Sustainability Dimensions

Defining sustainability dimensions is a major step in energy systems sustainability assessment. dimensions are used to investigate the technical, economic, social, and environmental sustainability of energy systems. Four (4) dimensions: technical, social, environmental and economic have particularly been highlighted to be highly important in the sustainability assessment for energy planning *(Afgan and Carvalho., 2004).* The effective indicators must meet characteristics reflecting a problem and criteria to be considered by showing how well the system is working. These indicators are necessary to reflect various aspects of the energy system for future energy scenario assessment.

a. Technical Dimension

The technical indicators are selected in the way to reflect the impact of these on energy supply technical performances. Production efficiency is defined as the ratio between the useful output of an energy conversion system and the input, it is adopted by several studies as indicator *(Afgan and Carvalho., 2004; IAE., 2007; Liu., 2014; Stein., 2013).* The various options under consideration being composed of different energy mixes are bound to have different technical performances. For the present study, the technical dimension is composed of the following indicators, namely: TCH1: production efficiency, TCH2: capacity factor, TCH 3: RP (resources potential), TCH4: reliability of the system, and TCH5: resources availability (toe). They refer to the efficiency of energy conversion and distribution, including fossil fuel efficiency for electricity generation, efficiency of oil refining, and losses occurring during electricity transmission and distribution.

b. Social Dimension

The energy system interacting with the surroundings needs to reflect the social aspect of the country *(Afgan and Carvalho., 2004)*. That interaction can be positive and/or adverse hence the great interest to investigate the social aspect of the options under consideration. Hence, the importance of the social dimension aspect in assessing energy system sustainability. The effective assessment of the social contribution in energy planning considers some social indicators. The availability of energy resources for greener and diversified energy generation is important. Creating jobs and generating income for energy to be affordable to the population although a high share of renewable energy in the mix might hinder the reliability of the systems due to the intermittent character of these energy sources *(Santoyo-Castelazo and Azapagic., 2014).* The following indicators are selected to assess the social impact of the Malian energy systems: SOC1 energy acceptability, SCO2 energy accessibility, SOC job creation, SCO4 energy affordability, and SCO5 people displacement.

c. Economical Dimension

Economic indicators are used to assess the economic impact on the evaluation of energy systems. The economic aspect has also been identified by various studies *(Afgan and Carvalho., 2004; Dombi et al., 2014; IEA.,2021, IAEA., 2007; Liu., 2014; Santoyo-Castelazo and Azapagic., 2014)* as a very important aspect in assessing long-term energy sustainability planning. It is also highlighted as an essential aspect of Malian energy planning by the country's Third National Communication Mali *(Mali NC., 2018).* Costs and return analysis, and payback period are used frequently, with a focus on the following indicators: ECO1: net import dependency (%), ECO2: fuel cost ($/GJ), ECO3: LVC USD/ KWH, ECO4: investment cost (€/KW), ECO5: payback period (year), ECO6: government support.

d. Environmental Dimension

Environmental indicators are selected to reflect the impacts of an energy supply system on environmental sustainability such as mitigating climate change and helping the country fulfil the NDCs (Liu., 2014). CO_2 emission has been defined by several studies to be a significant indicator for the sustainability assessment of an energy system along with Renewable energy fraction, and energy efficiency *(Afgan and Carvalho., 2004; Dombi et al., 2014; IAEA., 2007; Liu., 2014; Santoyo-Castelazo and Azapagic., 2014).*

The following indicators are used to assess the environmental sustainability of the energy systems: ENV1 Energy diversification, ENV2 Fraction of renewable energy, ENV3 Land demand/Rate of deforestation, ENV4 Emission, and Global warming potential.

3. Literature reviews: climate change impact on energy systems

Climate change has implications for both human beings and natural systems and could lead to significant changes in energy resources, production, and economic activity *(Raghuvanshi et al., 2008).* Energy systems are important infrastructures in many countries, and its disruptions can have serious economic implications *(Emodi et al., 2019).* Energy systems have been highlighted in most studies as the solution to mitigate climate change and provide economically feasible energy generation options. An increasing number of studies explored the impact of climate change and variabilities on energy systems these last decades. This review will cover work done on energy systems in terms of climate impact and projection, mitigation, adaptation and sustainability assessment.

Studies have considered the impacts of climate change on energy supply systems, energy demand, and the electricity market *(Schaeffer et al., 2012; Cronin et al., 2018 ; Mideksa and Kallbekken., 2010),* etc. *Rothstein et al., (2007)* looked at energy sector sensitivity to weather risks. The study highlighted a reduction in electricity production from thermal plants due to an increase in ambient air temperature, low water level, and higher water temperature. This was also identified as consequence of more frequent droughts and heat waves using the regional climate models for middle Europe. *Emodi et al., (2019),* identified a consistent increase in energy demand in Africa occurring as a result of climate change; a projected decrease in hydropower in North and Southern Africa, as well as a decrease in thermal production in western and southern Africa through a systematic scoping review on the impact of climate variability and change on the energy system. Various studies used the ensemble of CORDEX projection to determine future changes in wind energy resources in the Caribbean for the 21st century (*Costoya et al., 2019);* and wind energy resources in the coastal environment of the Black Sea. *(Rusu., 2019) ;Bartók et al., 2019)* projected changes in the European energy sector using climate projection dataset. *(Sawadogo et al., 2019)* examined how global warming may change the wind potential over the West African region. The study found a decrease in wind power density (WPD) projection at 1.5 °C for offshore wind and an increase in the potential on land. It is projected to increase with the increasing warming level. The study found an increase in the future wind speed in some cities (Abidjan, Lagos, Accra, and Dakar). Eventually, the study concluded the increase would not be enough to make some other West African cities (which are not viable for wind generation at present) viable for wind power generation (Guinean and Savannah zones) *(Sawadogo et al. 2019). Warnatzsch and Reay., (2019*) evaluated temperature and precipitation change in Malawi using CORDEX-Africa climate simulations. *Stanzel et al.,(2018)* also used the ensemble CORDEX climate project to evaluate the impact of precipitation changes on West African rivers. *Neher et al., (2017)* studied the impact of atmospheric aerosols on photovoltaic energy production in the Sahel region, particularly in Niger. The study found that on average daily global radiation and daily PV (polycrystalline module) yields were reduced by 14% and 13% respectively.

Solaun and Cerdá., (2019) identified the main climate threats and their impacts on different energy resources: hydro, wind, solar, and other energy technologies. Changes in rainfall patterns, floods, intense rain, and air temperature are identified as climate threats faced by hydropower, and impacts could vary from river flows and water level in the river, dams' safety, a decrease in power output, etc. The review also highlights inconsistency in projecting the impact of climate on the production trend. It concluded that changes in wind speed, the daily or seasonal distribution of wind, temperature, and extreme events are climate threats faced by wind energy and would result in a decrease in power generation. Solar energy would face challenges linked to changes in mean temperature, changes in solar irradiation and cloudiness, dirt, dust, atmospheric particles, and others leading to an efficiency drop of PV modules (0.5% for every 1 C increase in temperature), decreasing the efficiency of the cells and the power output.

Raghuvanshi et al., (2008) looked at the potential of renewable energy for climate change mitigation, sustainability, and energy supply options. The study identifies renewable energy as the solution to alterations in energy supply. Some studies *(Sawadogo et al., 2020)* have shown that the solar cell temperature is sensitive to ambient wind speed and relative humidity as well. The study presents renewable energy as an opportunity to expand and diversify the energy supply towards greater sustainability. *Falchetta et al., (2019)* identified droughts and consequences of water level reduction in Lake Volta as significant contributors to the observed and projected drop in hydropower generation and consequent power supply issues experienced in sub-Saharan Africa.

A number of studies focused also on the sustainability assessment of energy systems (sustainability of energy supply, sustainability of transmission, sustainability of energy resources, and sustainability of energy policies). *Zhu et al., (2020)* conducted extensive work on analysing the robustness of Japan's energy supply and the role of renewable energy. The study focused on energy security improvement and the government’s action to boost diversification and sustainability. *Tolnov and Rudolph., (2020)* reviewed renewable energy systems for sustainable rural development; the review examines the interplay between renewable energy and rural development in the context of energy transition. *Nam et al., (2020)* developed for a Korean case study a deep learning-based forecasting model for renewable energy scenarios to guide sustainable energy policy. The optimal scenario is assessed by considering its strengths, weaknesses, opportunities, and threats while also considering techno-economic-environmental domestic and global energy circumstances. *Umoh and Lugga., (2019)* worked on a study to contextualise hazard mitigation policy for electricity grids in the Sahel Region of Nigeria. *Curto et al., (2019)* evaluated the renewable energy mix to supply small islands in the Balearic Islands and Fiji. *Saavedra et al., (2018)* conducted an overview of system dynamics modelling applied in the renewable energy supply chain. Energy sustainability depends on various criteria called sustainability criteria. These criteria need to be considered in planning a sustainable energy system.

a. Climate models

Climate models are sophisticated computer simulations that strive to replicate the behaviour of the atmosphere, oceans, land, and ice, and their interactions over time. These models incorporate physical laws, chemical reactions, and dynamic processes to project how the Earth's climate might evolve under different conditions. Climate models use mathematical equations to describe how energy and matter interact in various sections of the ocean, atmosphere, and land. Numerical models (general circulation models, or GCMs) are physical processes in the atmosphere, ocean, cryosphere, and land surface and are the most advanced tools currently in use for global climate system simulation responses to increasing greenhouse gas concentrations (IPCC., n.d.). The models are used to determine both natural and human influences and how they will impact changes in the climate. These predictions and results suggest how to mitigate the effects of climate change. General circulation models (GCMs) are the most complex and precise models for understanding climate systems and predicting climate change. These models include information regarding the atmospheric chemistry, land type, carbon cycle, and ocean circulation (see: What Are Climate Models and how accurate there are *(Columbia*

University, n.d.)). Climate models come in a range of resolutions, referring to the level of detail and granularity. Higher-resolution models incorporate smaller geographic and temporal scales, capturing finer features of the climate system and allowing to capture of rapid changes in atmospheric and oceanic conditions. Spatial resolution pertains to the size of grid cells used to divide the Earth's surface in the model. Global climate models often have resolutions ranging from tens of kilometers to hundreds of kilometers, while regional climate models might have resolutions of a few kilometers or less. High-resolution models can simulate small-scale features like individual mountain ranges, coastal zones, and urban areas, which are crucial for understanding local climate impacts. Earth's surface is divided into a three-dimensional grid of cells in climate models, typically having a horizontal resolution of between 250 and 600 km, 10 to 20 vertical layers in the atmosphere, and sometimes as many as 30 layers in the oceans. The resolution of the model is determined by the grid cell size; the more finely detailed the model, the smaller the grid cell size *(IPCC., n.d.).*

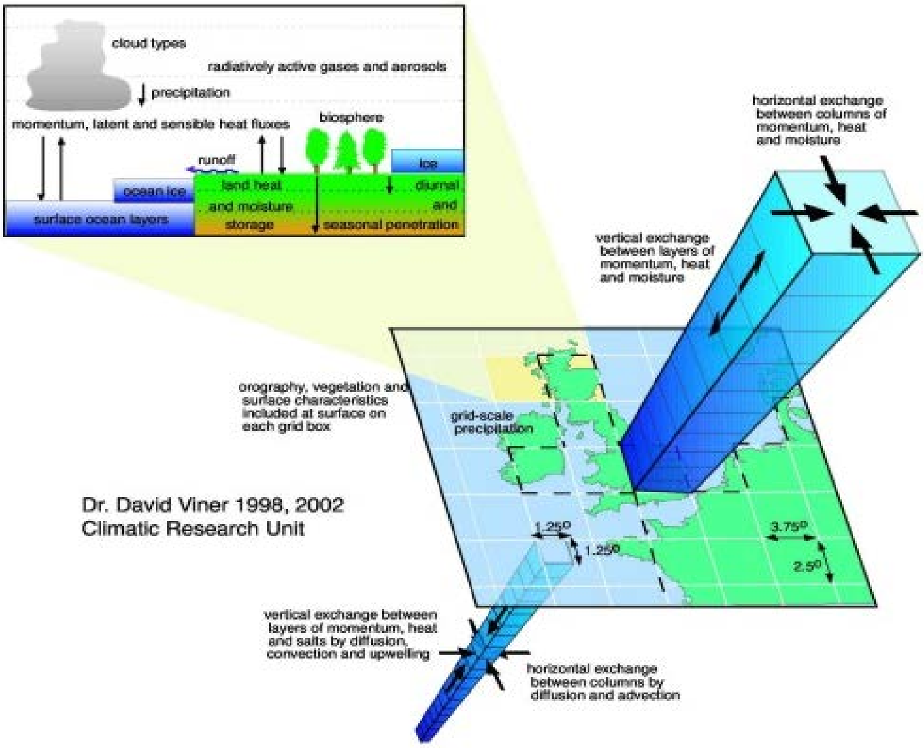


Figure 4: climate models output and resolutions (Earth and Environmental Data Science, n.d.)

b. Climate scenarios:

Climate scenarios are the foundation for climate impact studies *(Ministerrādet., 2012).* Climate change scenarios are projections of future greenhouse gas (GHG) emissions to forecast how vulnerable the world will be to climate change. Scenarios and pathways are employed to examine long-term approaches, investigate the efficiency of mitigation programs and comprehend the various potential futures. Climate scenarios are based on estimations of future population growth, economic activity, the structure of governance, social values, and patterns of technological change. They are intended to assist stakeholders in comprehending the decisions that will have significant impacts on climate change adaptation or mitigation *(Climate Change Scenario., 2023).* Reviews of these scenarios serve as the foundation for international goals for mitigating climate change through international bodies like the Intergovernmental Panel on Climate Change (IPCC), the Paris Agreement, and Sustainable Development Goal 13 ("Take urgent action to combat climate change and its impacts"). The Coupled Model Intercomparison Project Phase 5 (CMIP5) projections make use of these scenarios (Representative Concentration Pathways (RCPs)), which depict the atmospheric concentrations of anthropogenic GHG emissions by providing coherent ranges of potential changes in those emissions in the future. The IPCC has selected a trajectory for greenhouse gas concentrations (not emissions) called the Representative Concentration Pathway (RCP). Four pathways that describe different climate futures, all of which are considered possible depending on the volume of greenhouse gases (GHG) emitted in the coming years namely RCP2.6, RCP4.5, RCP6, and RCP8.5. The RCPs are labelled after a possible range of radiative forcing values in the year 2100 (2.6, 4.5, 6, and 8.5 W/m2, respectively) (Figure 5). RCP 2.6 projects a radiative forcing peak of 3 W/m2 before 2100, and then it declines. RCP 4.5 and RCP 6 project the stabilisation of the radiative forcing by 2100 of 4.5 W/m2 and 6 W/m2, respectively. Finally, RCP 8.5 projects a radiative forcing larger than 8.5 W/m2 by 2100 *(Moss et al., 2010; Ministerrādet., 2012; Representative Concentration Pathways., 2019).* RCP2.6 is a pathway where emissions peak and decline rapidly, leading to a lower radiative forcing level by the end of the century. On the other hand, RCP8.5 represents a scenario with high emissions and minimal mitigation efforts, resulting in a high radiative forcing level *(Huang et al., 2021).* In the study, two of them are considered: RCP 4.5 (median) and RCP 8.5 (pessimistic).

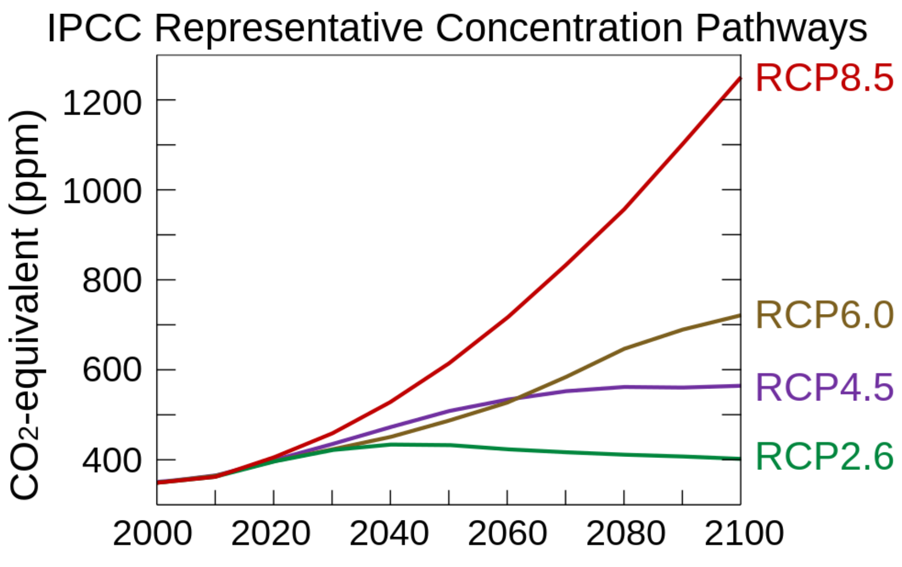


Figure 5: Presentative concentration scenarios RPCs

II.3. Climate Change Impact and Variability on the Energy System

1. Energy Generation and Supply in a Changing Climate Context

The energy sector can be impacted by changing climate conditions in various ways, both positively and negatively. Around 70% of all greenhouse gas emissions worldwide are related to energy use, while 26% of those emissions in 2004 were directly tied to power generation and heat delivery *(Mideksa and Kallbekken., 2010)*. To delay global warming, initiatives to cut down carbon emissions energy generation must heavily rely on renewable energy. However, due to their reliance on weather variables (such as temperature, wind speed, solar radiation, etc.), these energy resources are vulnerable to climate change *(Oka et al., 2020)*. The energy systems are set to be increasingly affected by climate *change (Rothstein et al., 2007)*, with direct effects on energy endowment, infrastructure, and transportation, as well as indirect effects through the economic sectors, with consequences on energy supply and demand (being the most obvious) *(Ebinger and Vergara., 2011)*. Temperature increases are expected to lower heating demands while increasing cooling demands *(Ebinger and Vergara.,* 2011). The efficiency of generation cycles and cooling water operations at fossil fuel, nuclear, and biomass-fired power plants may also be impacted by climate change. Although it may vary, it is hard to determine the generation potential of renewable energy without further, site-specific research. Variations in rainfall may benefit or hurt hydropower generation at various times, and overall, some places may experience future lower generations. Solar generation may not be significantly affected *(Ebinger and Vergara., 2011).* Water (precipitation) variability could lead to inefficiencies in energy and water use. Local changes to the wind regime may have a favourable or negative effect on wind generation. Modifications to agricultural practices may have an impact on the production of biomass and biofuel. Infrastructures for the transfer of energy (for power, oil, and gas) are exposed to a variety of weather conditions, including wind gusts, storms, icing, landslides, and rock falls brought on by storms, land movements, siltation, and erosion processes, as well as changes in water basins *(Ebinger and Vergara., 2011).* It is reported that for a 1ºC increase in temperature, energy consumption is expected to change within the range of 5%. Depending on the technology, many factors might cause climate change to affect the availability of energy *(Mideksa and Kallbekken., 2010).* These effects are likely to differ between and within regions (IPCC, 1991). Therefore, policymakers cannot provide a good adaptation plan without integrating both sectors as parts of a single strategy. The weather (climate) variations and their effects on the energy resources reported in the literature are gathered in the following table (Table 1).

Table 1: climate threats on the different renewable energy resources

Climate Threats	**Impacts**	**Resources Impacted**	
Temperature increases	Can modify soil conditions, reflecting on crop fertility and productivity, which may be offset by higher photosynthetic activity in some cases;	Biomass	*(Solaun and Cerdá., 2019)* *(Ebinger and Vergara., 2011)* *(Schaeffer et al., 2012)*
	Each plant has a temperature range suitable for its growth and an alteration in regional temperature could cause modifications in regional agricultural profiles;		
Higher CO2 levels	Can also have a positive impact on crops with higher sensitivity to CO2, improving photosynthesis		
Droughts, frosts and storms	Can also affect crops.	Biomass/ Biogas	
Changes in precipitation/ increases in temperature levels.	This leads to higher evapotranspiration rates		
Increased temperatures	Have effects on the metabolism of insects, accelerating their reproduction and increasing the incidence of pests		
Change in rainfall patterns	Can impact river flows and water levels affecting production	Hydropower	

Change in Air temperature	Could increase surface evaporation, reduce water storage and power output		
Changes in mean temperature	Could lower the capacity of underground conductors and increase soil temperature		
	This could negatively affect the efficiency of the cells and therefore the power output	Solar Energy	
Changes in irradiation and cloudiness	Could affect solar power output		
Wind speed	Strong wind may cause material damage from debris and need for cleaning, but they can also cool down the modules, increasing efficiency and output		
Changes in Precipitation	Could reduce efficiency (less solar radiation)	Wind energy	
Changes in wind speed	Can reduce generation		
Changes in temperature	This will lead to slight declines in air density and power output		

2. Climate Change Impact Studies

Addressing the impacts of climate change on energy demand patterns, long-term energy consumption, and energy production considers simulated future projections and historical climate statistics of global climate models (GCMs) *(Wang et al., 2020).* Climate change's impact on power demand and supply is typically studied using the concepts of heating-degree days and cooling-degree days *(Mideksa and Kallbekken., 2010).* The best available baseline to assess future climate changes is the observed climate in the recent past, as it provides essential historical data and trends to help us understand and project potential future climate scenarios. Studying the observed climate in the recent past provides valuable information for understanding the potential impacts of climate change on various ecosystems and communities *(Ebinger and Vergara., 2011).*

a. Model evaluation:

Evaluation of climate models (to represent the observed behaviour of past climate) is a necessary step to take to prove confidence of future projections. The most straightforward approach to evaluating climate models is to compare simulated quantities (e.g., global distributions of temperature, precipitation, radiation, etc.) with corresponding observationally- based estimates. No individual evaluation technique or performance measure is considered superior; rather, it is the combined use of many techniques and measures that provides a comprehensive overview of model performance *(Flato et al., 2013).* A significant development since the assessment report four AR4 is the increased use of quantitative statistical measures, referred to as performance metrics. The use of such metrics simplifies the synthesis and visualisation of model performance.

b. Bias correction to improve the agreement of simulations with observations

The General Circulation Models (GCMs) that provide climate simulations usually suffer from biases in their output *(Ravestein et al., 2018).* These can affect the accuracy of their predictions. Bias refers to the systematic overestimation or underestimation of model outputs compared to observed data. Positive bias indicates that the model consistently overestimates the observed values, while negative bias indicates underestimation. The biases can arise from a variety of factors, such as the simplifications made in the models, the limited resolution of the grid used, and the uncertainties associated with the input parameters. Accurate predictions are essential for understanding and mitigating climate change impacts. Prior to performing any regional climate change impact analysis with these projections, it is thus important to correct these biases. Several methods are applied to make this correction. Cumulative Distribution Function-Transform (CFD-t) method is a non-parametric quantile mapping-based technique that accounts for climate change (or changes in the underlying distribution). It corrects model values in a future period given observations and model data in a reference period *(Bartók et al., 2019).* It is often easy to demonstrate whether a certain prediction is accurate *(UK., 2007).* Hindcasting or testing models' capability to simulate the future climate (including variability and extremes) is an important part of model evaluation. Assessing climate models involves evaluating their performance, accuracy, and reliability in representing the Earth's climate system. The evaluation of downscaled climate projections requires, one to assess how large-scale predictors are simulated and second to assess how well the downscaling itself performs. In a climate change context, both assessments must address not only the performance of the present climate but also the performance of past climatic changes and potential future climates *(Maraun et al., 2018).* The easiest method for assessing the precision of climate models is to compare their outputs with observational data. There are many ways in which this comparison can be undertaken, each having limitations *(Warnatzsch and Reay., 2019).*

c. Model validation

Statistical tools play a critical role in the validation and assessment of climate models' performance. The commonly used statistical tools are root mean square error (RMSE), mean bias, correlation coefficients, and standard deviation. Those statistics could be represented in Taylor diagrams. These metrics enable us to quantitatively assess the agreement between model simulations and observed climate data, allowing us to identify areas for improvement. These provide a succinct statistical analysis of the degree of pattern correspondence between the modelled data and observed data in terms of Pearson's correlation, root-mean-square error, and the ratio of variances. The Taylor diagram is a popular and useful tool in the validation of climate models (*Gleckler et al., 2008; Loikith et al., 2015).*

d. Root mean square error (RMSE)

Root Mean Square Error (RMSE) is a widely used measure of the differences between modelled and observed values. It calculates the square root of the average of the squared differences between each modelled value and its corresponding observed value. Lower RMSE values indicate better agreement between model and observation.

e. Mean absolute errors (MAE)

The mean absolute error (MAE) is another common statistical metric used to assess the accuracy of climate models or the performance of these models. It measures the average magnitude of errors, or the absolute differences between the predicted values and the actual observed values.

e. Correlations

Correlation Coefficient (r): The correlation coefficient measures the strength and direction of the linear relationship between modelled and observed values. A correlation coefficient close to one (1) indicates a strong positive linear relationship, while a value close to one (-1) indicates a strong negative linear relationship.

Coefficient of Determination (R2): The R2 statistic shows how much of the variance in the observed data the model can account for. Higher numbers suggest a better fit between the model and the observation, and they range from 0 to 1.

f. The Taylor Diagram

The Taylor diagram is a graphical summary of multiple statistical measures that capture the agreement between model output and observed data. It compares different climate models or model versions. It helps identify model biases and areas where models may need adjustments or further development. The diagram offers an easily interpretable visual summary of a model's skills, making it valuable for both scientists and stakeholders, especially for climate model validation. It aids in assessing the reliability of climate models when projecting future climate scenarios. It provides a holistic view of a model's performance by condensing several metrics into a single plot. This compact visualization tool simplifies the assessment process and makes it easier to compare different models or model simulations

II.4. Gaps in the literature review

Various studies have taken a close interest in the impact of climate change on energy systems and energy sustainability assessment. In Sub-Saharan African regions, little attention has been devoted to that topic; fewer address this issue in Sahelian countries such as Mali, known to be most vulnerable to climate change and to be an energy-poor country. Studies have examined the implication of these impacts and changes on the sustainability (sustainable supply) of the energy systems under changing climate scenarios. Although research on renewable energy has focused on its enormous potential to address climate change, meet energy demand, and provide a sustainable supply of energy, relatively little has been done to examine how climate change affects renewable energy and how intermittent these resources are in providing a sustainable energy supply in Mali. Consistent climate impact on energy resource projection and the possible disruption of the energy supply in the West African region particularly in Mali are still very scarce in the literature. Therefore, studies on the sustainability of energy supply considering climate change's impact on renewable energy resources and their intermittency (climate mitigation requires the share of RE increase in the national energy supply) are needed.

II.5. Conclusion

There has been a clear growing interest in the field of climate change's impact on energy systems, demonstrated by the interest of the country in energy transition, energy supply sustainability and the various political wills to fight against climate change, global warming, and greenhouse gas emissions. This cannot be foreseen without a clear path of energy systems evolution and clear changes that may occur with them in the future. Thus, to adequately quantify the impact that climate change will have on energy systems, a clear understanding of the energy systems and their evolution under different climate scenarios (scenarios) is required. The government and policymakers need to access credible literature that can provide them with insights into the impact of climate change on energy systems, which will help them formulate effective long-term energy polices for the country. The sustainability energy systems, how these would affect the country's long-term energy planning is essential information that should be provided by literature to guide policymakers, governments, and energy practitioners of the country in planning for sustainable, affordable and resilient future energy systems for all.

Chapter III: Current Energy Situation of Mali

III. 1. Introduction

Considering the current global temperature increase, energy systems have a very important role to play in achieving global sustainability. In its NDCs Mali plans to reduce it greenhouse gas emissions from the energy sector by about 31% by 2030. To achieve this ambition, it is important to look at the country's current energy situation. In this section the Malian energy situation is assessed; energy demand, the supply and the various policies and strategies in place are also considered. Additionally, transition and diversification policies are assessed. The present section of the study focuses on the Malian energy current situation. It looks in detail at the Malian energy sector, and the various policies and strategies put forward for the sustainable future development of this sector. It considers domestic energy (also called cooking energy) and the electricity sector. It looks at the energy resources, energy supply, energy production, and consumption. It also looks at the different energy policies in the country.

Mali is a landlocked country located in the Sahelian region of West Africa, with a population of 19.6 million in 2018 *(IRENA., 2019).* Mali is considered one of the largest countries in the region, with a surface land area of 1,241,248 km2, of which 51% is desert and 4% arable land *(AfDB., 2015).* Table 2 summarises the essentials of the Malian energy related key indicators.

Table 2: Malian energy system overview for 2018. Data are obtained from DNE

Key indicators	**Units**	**Value**
Population	(millions)	19.6
Energy production	(ktoe)	5253.936
Installed capacity	(Mwe)	1080.18
Net energy import	(ktoe)	1720.233
Total Primary Energy Supply (ATEP)	(ktep)	6928.113
Electricity consumption	(MWh)	3085828.640
ATEP/Population	(toe/inhabitant)	0.357
Electricity consumption per capita	(MWh/capita)	0.159
Share of renewables in ATEP	**%**	75.8%
Share of renewables in the production of electrical energy	**%**	39.0%
National electrification rate	**%**	47.9%
Rural electrification rate	**%**	7.3%
Average daily LPG consumption per household	(kg/household)	0.013

Energy intensity of the industry sector	(toe/ Thousands of US$ "base year")	0.098

III. 2. Current Energy Situation of the Country

The primary energy supply in Mali is biomass, which supplies 74% of all energy consumed. Mali’s oil and gas subsector is characterized by total dependence on petroleum imports, which represented 22% of total imports in 2010. This is exposing the economy to the volatility of fossil fuel prices. It also puts the economy under foreign reserve pressure, including the development of the energy sector. EDM$_{\text{SA}}$ is the utility that generates, transmits, and distributes electricity in Mali. Biomass is the main energy source for most of the population 74%, while fossil fuels contribute 22% of the energy supply and hydro contributes 1% (excluding electricity trade). Electricity demand is growing extremely fast (about 10% per year in recent years), driven by domestic consumers, the industrial and mining sectors. Electricity access rates are low but improving, 17.19% in the rural sector, compared to 66.80% in urban centres (*African Development Bank Group & Green Mini-grid Market Development, 2018)*

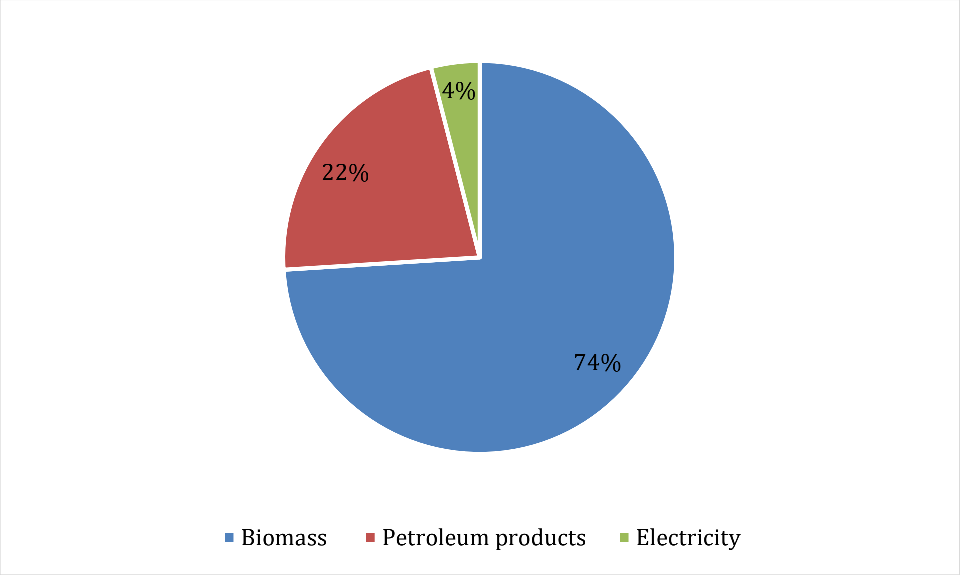


Figure 6: Malian Energy Supply

1. Malian Energy Sectors

The energy situation of Mali has long displayed a high dependence on petroleum and petroleum products imports, and high consumption of biomass energy (wood and wood products) from its natural forests. The main energy source is biomass, extensively used in cooking in the residential and commercial sectors. Access to modern and clean fuels for cooking remains very low; usage of cooking energy and clean cooking equipment (improved stoves, LPG, modern biomass briquettes, and electricity) remains as low as 2% and 3% for rural and urban areas, respectively *(IRENA., 2019).* EDM$_{SA}$ is in charge of electrification (generation, transition, and supply) in urban and peri-urban areas. Rural electrification is under AMADER's (the Malian Agency for Rural Electricity and Domestic Energy) responsibility. Aside from those two, several other institutions are involved in the Malian energy sector (Appendices 2). The Ministry of Energy and Water, as well as its associated organizations *(IRENA., 2019).*

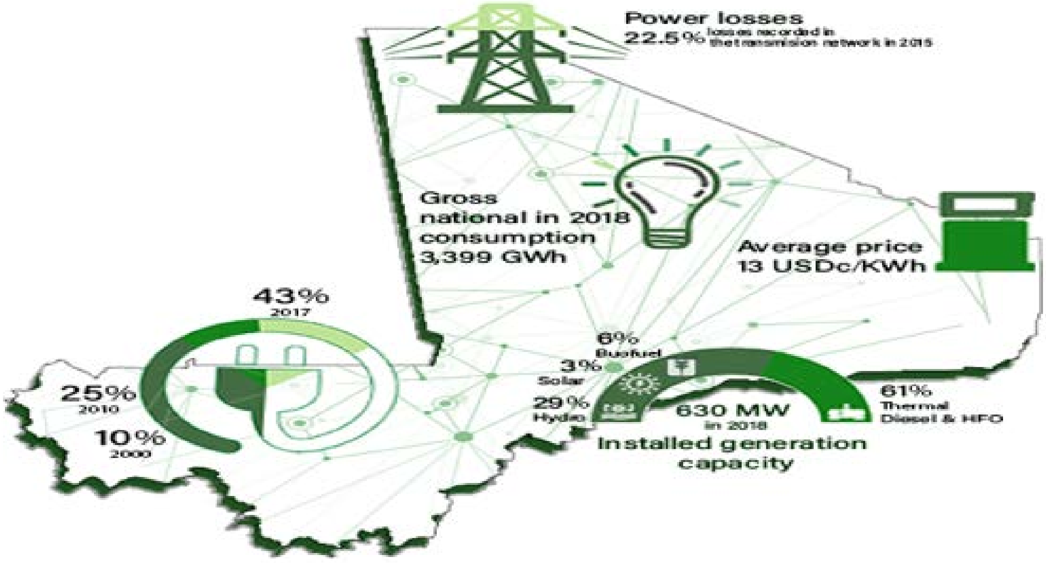


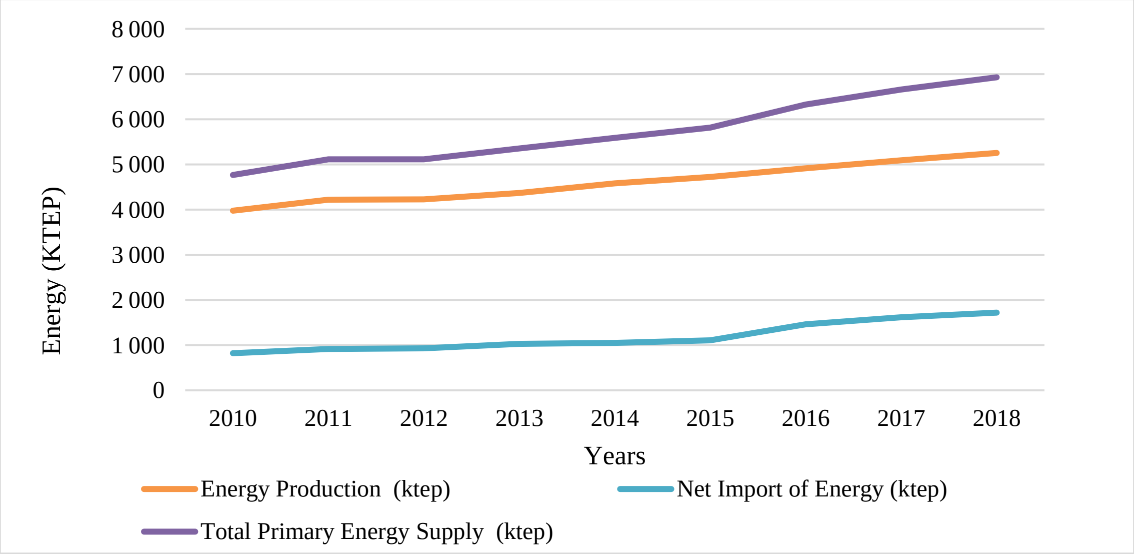
Figure 7: key indicators of the Malian energy sector (reproduced from (IRENA., 2019))

2. Energy demand

There is an unexpressed and largely unsatisfied demand for electricity in Mali, both for domestic users and for large industries, particularly those in the mining *sector (AfDB., 2015)*. Energy demand is set to increase with a growth rate of 15 % by 2025 mainly driven by rapid population growth, urbanisation, and economic growth *(African Development Bank Group & Green Mini-grid Market Development., 2018).* Despite the tremendous efforts and progress achieved, the electrification rate remains very low, especially in rural areas (17.19% in the rural sector, compared to 66.80% in urban centres. Power shortages are more common and longer, especially during the hot months of March to June. The difference between energy demand and supply keeps expanding year after year. This makes energy planning a national priority and the opportunity to integrate renewable energy off-grid systems in the mix is more critical to exploring policies to fill the demand gap.

3. Energy supply

In Mali, about 74% of household energy or domestic energy (cooking and heating) needs are satisfied by biomass resources (wood, charcoal, and animal waste); fuel wood for domestic activities is provided by the immense but surely declining Malian forest reserve, covering about 31 million hectares (representing 25% of the country's surface area). Electricity is supplied by EDM $_{SA}$ (Energie du Mali), the main electricity company, and other small local organizations in the private sector supported by the Malian Agency for Energy Development Domestic and Rural Electrification (AMADER). Mali is a key member of the Senegal River Basin Development Organisation shared by Guinea, Mali, Mauritania, and Senegal, and an equally important member of the West African Power Pool (WAPP), a specialised institution under ECOWAS. The WAPP is a Regional Electricity Regulatory Authority responsible for cross-border electricity exchange regulation *(IRENA., 2019)* with the purpose of meeting the increasing energy demand in the various West African countries by sharing electricity across the region. It aims at integrating the operations of the national power systems of the countries into a unified regional electricity block. The Malian electricity imports from neighbouring countries (now only from Cote d'Ivoire) represent 29.4% (50 MW) *(EDM$_{SA}$., 2022).* The country imports electricity from Côte d'Ivoire through the interconnectors. The share of electricity imports from Cote d'Ivoire to meet demand is set to increase shortly in the near future.



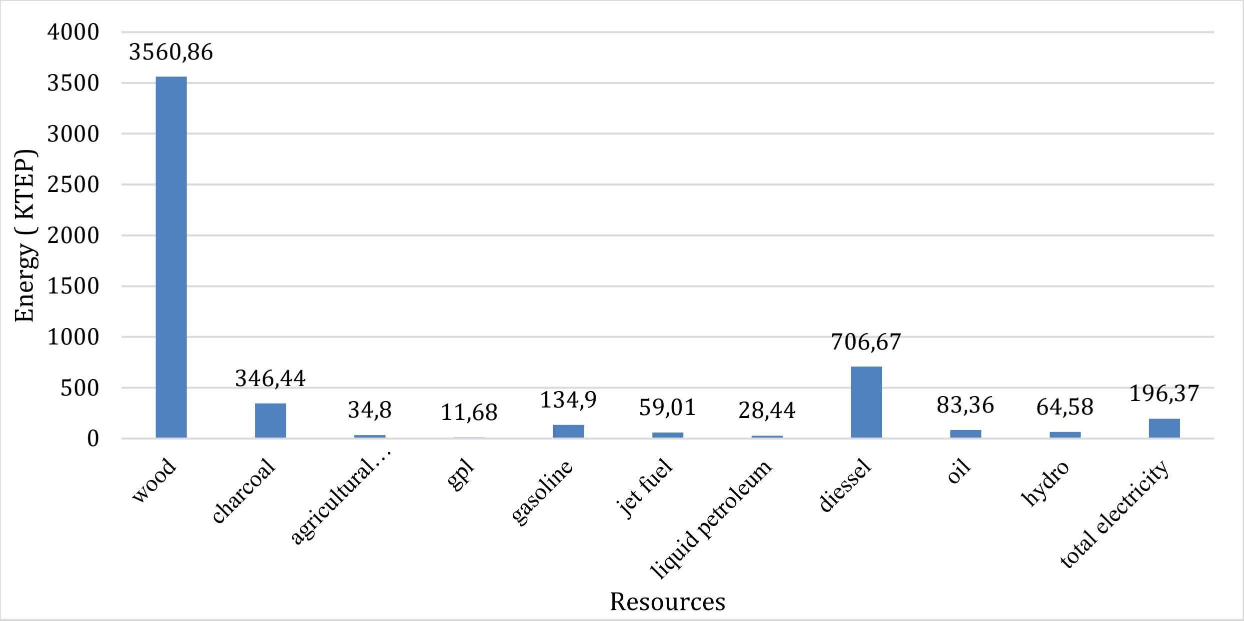
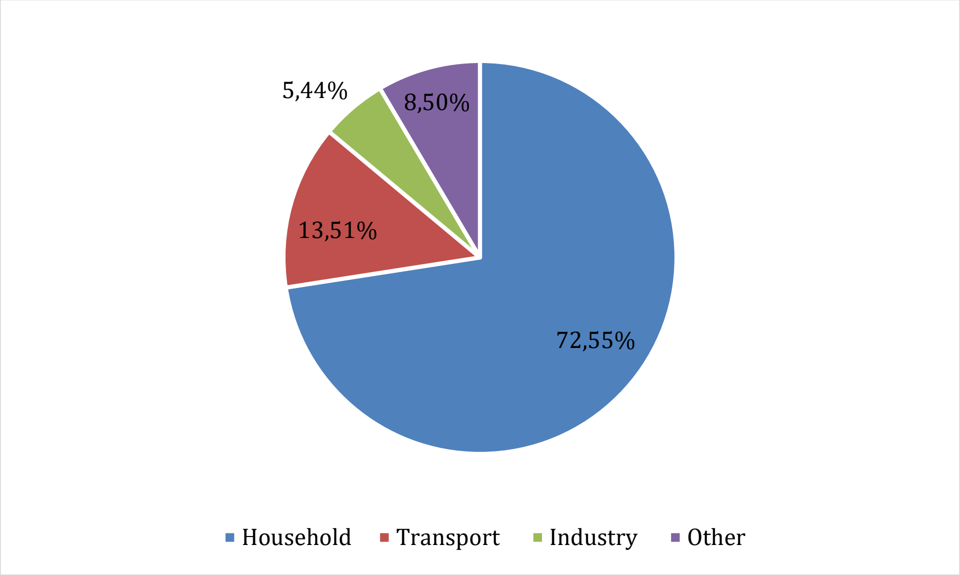


Figure 8: total national energy supply by energy resources of Mali

4. Final energy consumption:

Electricity, biomass, and petroleum products, with respectively 4%, 74%, and 22% consumed in 4 activity sectors: household, transport, industry, and others, Figure 9.



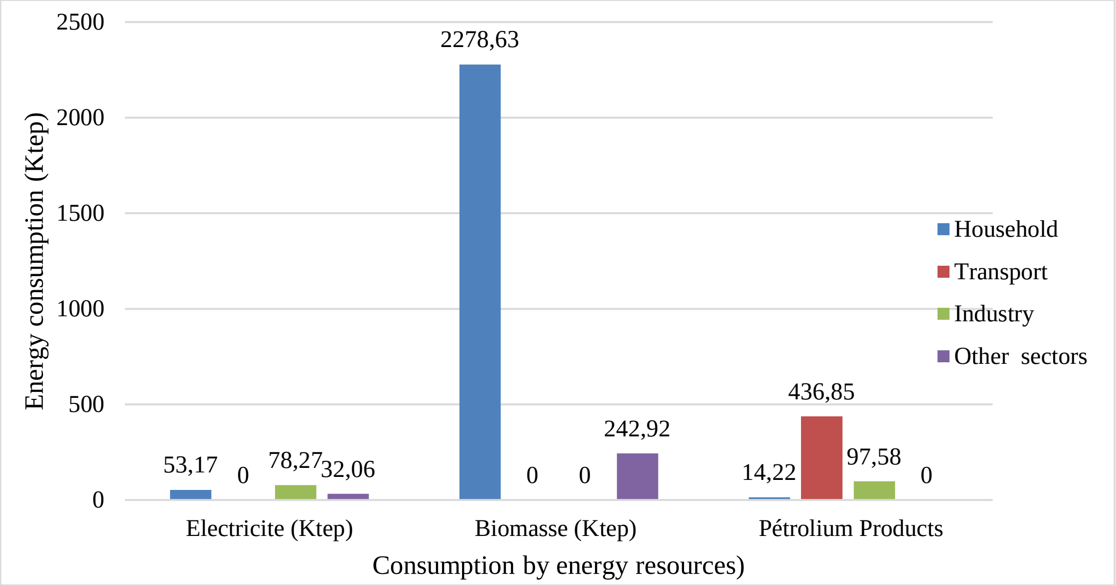


Figure 9: Share of National energy consumption by sector in percentage

The per capita final energy consumption of the country is 92.17 MWh/habitant, which is extremely low compared to an average of 116 kWh in the ECOWAS countries *(PANER., 2015)*. In 2014, the household had the highest energy use share of 2346.02 ktoe, corresponding to 73.55% of the total energy use, followed by the sector of transport with a share of 13.5%, the industry with a 5.4% share, and the rest of 8.5% for other end-use sectors (Figure 9). Biomass utilization has been increasing with time and demography (Figure 10), which is driving deforestation and the reduction of forest coverage in the country.

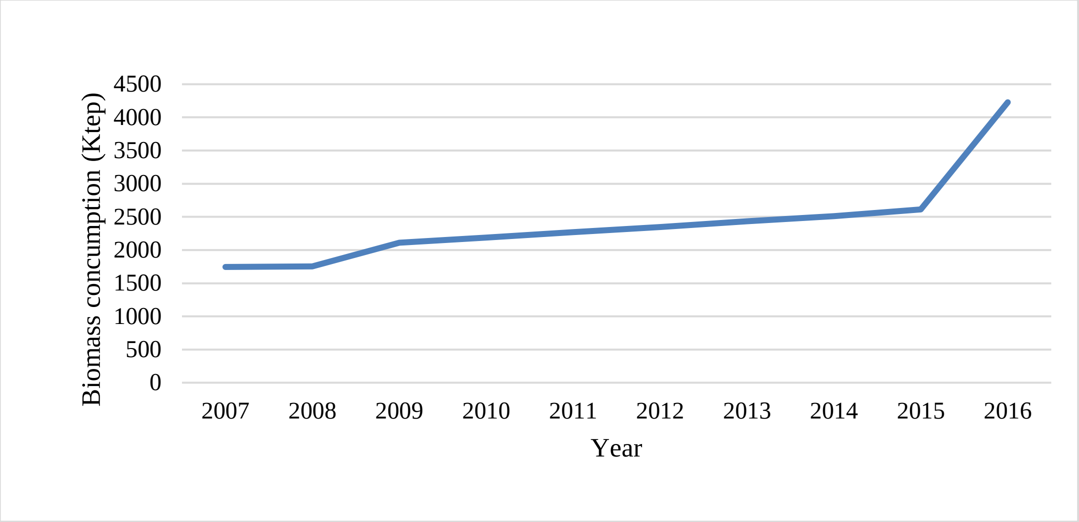


Figure 10: biomass consumption

5. Energy Generation and Transmission

a. Generation:

Hydropower and thermal are the main power generation resources. The major share of electricity produced in Mali comes from hydropower and thermal resources, and recently, hybrid (solar/diesel) and small-scale decentralized solar photovoltaic (PV) systems have been increasingly installed since 2011 *(EDM$_{SA}$., 2022).* The generation mix has gradually shifted in recent years from hydro-dominated production to a nearly equal share of thermal (fossil) power generation. Hydroelectricity is produced from large-scale interconnected hydropower plants installed on the rivers Niger and Senegal *(Nygaard et al., 2012).* AMADER is the regulator for rural electrification and serves as the energy regulatory authority outside of urban centres *(ADBG & GMMD, 2018).* Hybrid (solar/diesel) and small-scale decentralized solar photovoltaic (PV) are also very important energy production sources from renewable sources. Excluding large hydropower, renewable energy (solar and wind) shares remain very low in the country mix *(African Development Bank Group & Green Mini-grid Market Development, 2018).* The country benefits from a 30 MW minimum guaranteed capacity from Côte d'Ivoire, which has been raised to 50 MW in recent years (EDM, 2017). In 2017, imports from Côte d’Ivoire reached 333.18 GWh, 16% over the total electricity generated to supply the national grid. *(IRENA., 2019).*

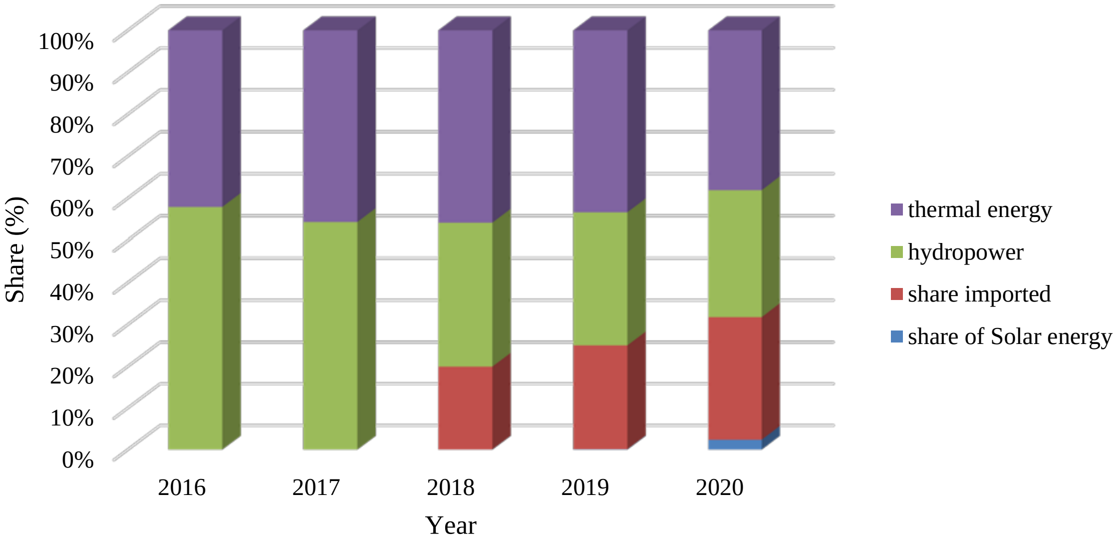


Figure 11: Share of electricity (produced from hydropower, solar, thermal, and imported)

Table 3 :Installed capacity (MW) (DNE)

Years	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**

Interconnected national grid	358	420.6	453.6	463.2	520.2	550.2	603.2	670.2	720.2
Isolated power plant	68.1	67.4	75.5	70.3	80.3	90.1	89.7	101.8	112.32
Total	426.1	488	529.1	533.6	600.5	640.3	719.9	772.0	832.52

b. Transmission:

Energy du Mali sa (EDM.sa) is the main actor involved in the power sector in Mali (*African Development Bank Group & Green Mini-grid Market Development, 2018; SE4ALL.,2019)*. It is thus the only responsible for power generation, transmission, and distribution in urban and peri-urban areas. Electricity produced by EDM $_{SA}$ through thermal and hydroelectric power stations is supplied through two components: The Generation-Transmission-Distribution-Sale (GTDV) component and the Purchase-Transmission-Distribution-Sale (PTDS) component as it can be seen in figure 12. The GTDV component comprises an interconnected network (IR) whose production system combines thermal and hydroelectric power stations and serves several localities, including Bamako, and isolated centers (IC) whose production system consists solely of thermal power stations *(Durable., 2017)*. The national grid has a large but declining share of hydroelectricity, but both isolated centres and large captive generators rely exclusively on fossil fuels to satisfy the energy needs. The international electricity trade will play a growing role in the next few years. In rural areas, a decentralized approach is being pursued, allowing private energy service companies to operate *(AfDB., 2015).*

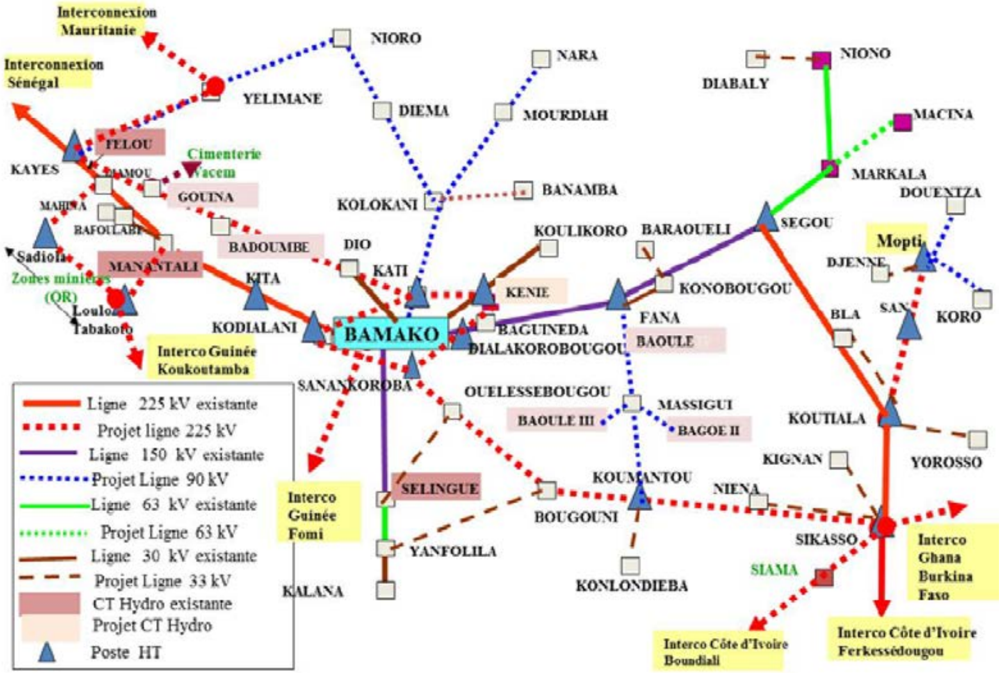


Figure 12: The Malian power transition scheme (EDM$_{SA}$., 2022)

The interconnected system, which is owned and managed by EDM $_{SA}$, is dominated by hydroelectricity, mainly generated by the Manantali Dam (of which Mali owns 104 MW out of the total 200 MW) and Sélingué (46 MW). Hydroelectricity represented 60% of all electricity produced in 2012, while the rest was generated by diesel or heavy-fuel power stations. *(AfDB., 2015).* The interconnected network (RI) serving thirty-five (35) localities includes the capital Bamako, thirty-three (33) isolated centers (CI) of production and autonomous distribution per locality and two (2) centers connected to the medium-voltage network of Côte d'Ivoire *(EDM$_{SA}$., 2022).*

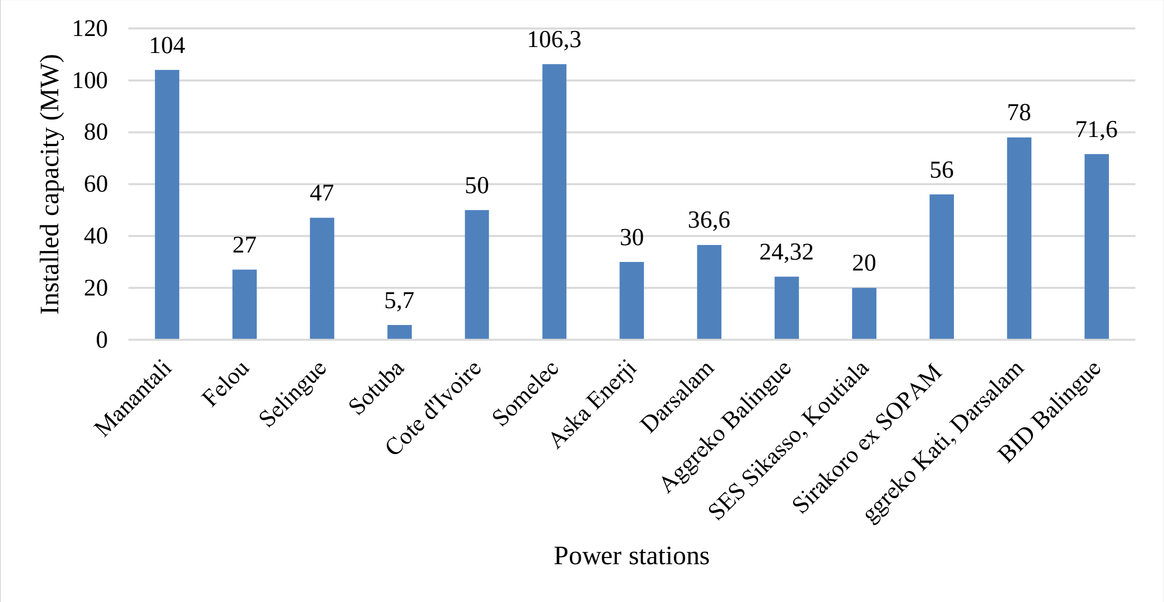


Figure 13: EDM $_{SA}$ National Grid connected Stations the integrated system

The regional interconnection electricity networks (without referring to the source of energy used upstream, for example, gas for the interconnection with Côte d'Ivoire) *(PANER., 2015)* The gross production and electricity purchases of the EDM$_{SA}$ group fell from 2,412.62 GWh in 2019 to 2,595.18 GWh in 2020, a growth rate of 7.57% against 8.69% in 2019, explained by a slowdown in economic activity *(EDM$_{SA}$., 2022).*

The isolated systems are equipped mainly with diesel generators or, in other cases, with hybrid systems powered by diesel and solar photovoltaic. The total installed capacity is 90.11 MW.

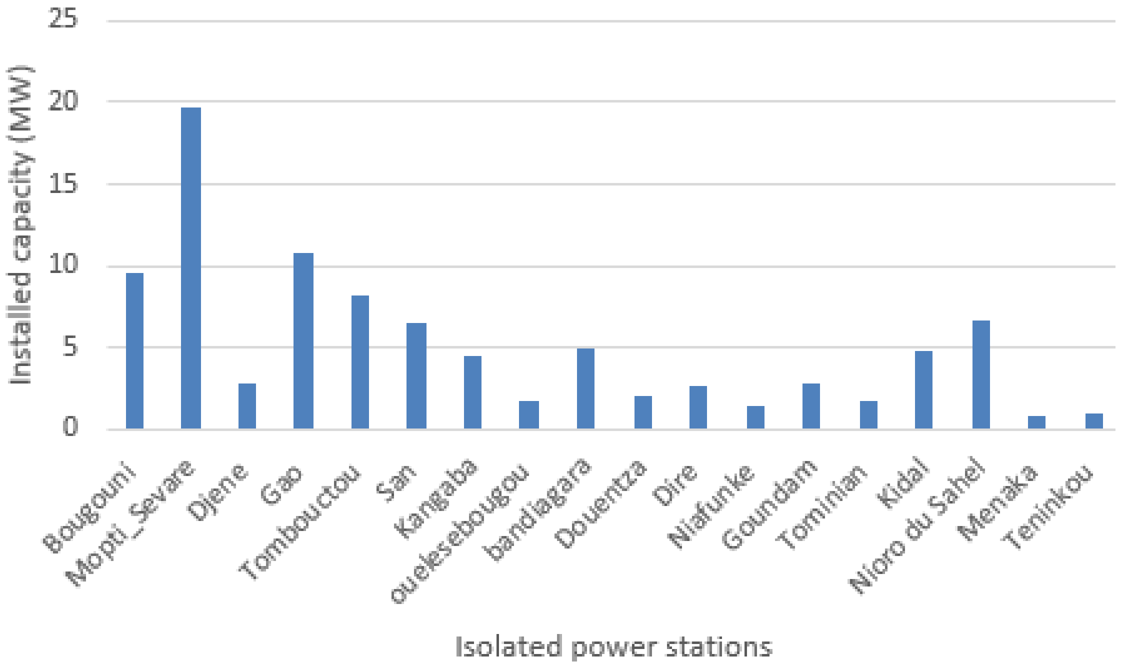


Figure 14: Power in isolated (MW) in production centre (2016)

6. Energy sector challenges:

The Malian energy system (as the case is for several sub-Saharan countries) faces quite several challenges. The challenges are quite diverse and similar in various ways, including some of the most prominent ones described in *(Mercedes and Cantarero., 2020; SE4ALL., 2019).* The rate of access to electricity improving but remains below expectations, particularly for the rural areas of the country. The heavy reliance on petroleum products remains stronger and keeps growing with economic growth, car ownership, rapid population growth, and urbanisation, which represent availability and price risks due to the landlocked nature of the country. The important share of thermal electricity generation leads to higher electricity production costs per kWh despite the important hydro and solar potential of the country. Unreliable power networks and systems: leading to load-shedding, i.e., forced, planned, or partial power outages. High price differences in energy and electricity between different rural areas and urban areas are linked to the distances travelled to obtain energy. Furthermore, the High reliance on diesel and diesel mini-grids, poor performance of these systems, Lack of investment in the sector, maintenance problems of several large hydroelectric power stations, the weak financial situation of EDM_{SA}/the country requiring the government to continue to subsidise the energy sector, and most importantly the increase electricity demand (more than 10% on average per year).

The need for regulatory framework encouraging rapid, large-scale development of energy renewables and energy, the high energy intensity of the country. Wood fuel (fuel wood and charcoal) consumption domination of the total final energy consumption, predominating in rural areas for cooking and lighting, particularly in the residential sector, which leads to worrying deforestation and justifies the need of improved stoves and modern means (clean energy resources, efficient cooking stoves) of cooking, which are often unavailable and costly. These are some of the important challenges to the Malian energy system sustainability.

7. Energy potential in Mali

a. Fossil fuel

To date, studies or exploration in Mali have revealed no proven fossil fuel resources or oil reserves that await extensive exploration in the northern and eastern parts of the country *(IRENA., 2019).* The country currently imports all the petroleum products consumed (transport and generation of electricity) *(Fronteras., 2016).*

b. Renewable energy

Mali has vast and untapped natural and renewable energy resources. Over the years, several studies have been undertaken to map the country's renewable energy resource potential. The most famous of which represents a series of studies undertaken under funding provided by the Danish International Development Agency (DANIDA) under the heading of the feasibility of renewable energy resources in Mali *(Nygaard et al., 2012).* The studies focused on a thorough assessment of the potential of renewable energy resources in Mali and the economic feasibility of the deployment of these resources. The studies covered five (5) main reports: analyses of the potential for sustainable cassava-based bio-ethanol production in Mali, agricultural residues for energy production in Mali, Pre-feasibility study for an electric power plant based on rice straw, estimates of wind and solar resources in Mali, screening of feasible applications of wind and solar energy in Mali, using the wind and solar maps for Mali.

The renewable energy resources in Mali preliminary mapping *(Nygaard et al., 2008)* and Using modelling, satellite images, and existing global datasets for rapid preliminary assessments of renewable energy resources: The case of Mali *(Nygaard et al., 2010).* Evaluating solar and wind energy potential with Screening of feasible applications of wind and solar energy in Mali: Assessment using the wind and solar atlas for Mali *(Nygaard et al., 2012)* and feasibility of wind power integration in weak grids in non-coastal areas of sub-Saharan Africa: the case of Mali *(Nygaard et al., 2017).* and modern biomass use in electricity production with agricultural residues for energy production in

Mali *(Nygaard et al., 2012)*, a feasibility study for an electric power plant based on rice straw *(Fock et al., 2012)*, and lignocellulosic residues for the production of electricity, biogas, or second-generation biofuel: A case study of the technical and sustainable potential of rice straw in Mali *(Nygaard et al., 2016).*

c. Solar Energy:

There is significant solar energy potential in the countries, especially in the northern part. The country has one of the highest solar energy potentials in the West African region, with irradiation of about 5–7 kWh/m^2 per day and a period of sunshine of around 10 hours per day well distributed over the country *(SE4ALL., 2019).* There is substantial variation between north and south due to the seasonal differences in cloud cover and the position of the sun.

f. Wind energy:

The wind energy potential varies over the country from speeds as low as 3 m/s (not ideal for wind power generation) to 7 m/s *(Consumption & Resources., 2016).* Wind speeds greater than 5 meters per second prevail in the central and northern parts of the country at above 16 degrees' latitude, from Mopti northwards, including in the towns of Timbuktu and Gao *(IRENA., 2019).*

g. Hydropower potential

Mali is home to the inner delta of the Niger River, which runs through nine countries in the region and serves Mali as the principal source for electricity generation. Rivers Niger and Senegal are the main rivers that allow Mali hydropower production. The current identified hydroelectricity potential is estimated to be around 1150MW, of which 840 MW remains still available. The identified exploitable hydropower potential (only 22% exploited on 1150 MW) on some twenty sites with an annual average production corresponding to about 5,600 GWh, of which only four (4) sites are fully installed. Félou (60 MW), Sotuba (5.2 MW), Sélingué (44 MW), and Manantali (200 MW) have a total estimated generation of 1043 GWH/year *(Durable, 2017; Rapport & Climatiques., 2018).* The undeveloped potential can be divided into three large groups: sites at the feasibility study stage (150 MW); sites at the pre-feasibility stage (342 MW); and sites at the reconnaissance stage *(150 MW) (IRENA., 2019; SE4ALL., 2019).*

h. Biomass energy

Biomass is used in Mali, particularly in the form of fuel wood and charcoal, for cooking and heating purposes. Fuel wood is the most important form of energy and is highly used in the country, particularly in the residential sector. Fuelwood and charcoal come from the national forest potential, whose total capacity was estimated in 2010 at 21 million hectares (standing volume of 308 million m3), including forests (12.5 million ha, average productivity of 20 m^3/ha) and other wooded land (8.3 million ha, average productivity of 7 m^3/ha) Consumption is in the order of 7 million tonnes of wood per *year (Fronteras., 2016).* Biomass resources used as energy in Mali also concern agricultural residue, Jatropha (for vegetable oil), Typha Austral, water hyacinth (invasive plants colonising irrigation canals), residues from sugar production (bagasse), and animal waste already used for cooking and heating purposes in some rural parts of the country. Residues available in sufficient quantity and concentration for energy recovery come from cotton hulls and cotton stalks, rice straws, and other cereals (peanuts, maize, corn, millet, etc.). The possible uses of these biomass resources are multiple: production of briquettes (organic charcoal), biogas generation (anaerobic digestion) for domestic purposes, or use for the generation of electricity. The choice depends on the quantities generated, the quality of the residues, and the current needs. Nearby energies or possibilities of connection to the central network *(Nygaard et al., 2016).*

8. Energy crops

In Mali, biofuels encompass bioethanol from the sugarcane industry as well as jatropha oil. The production of sugarcane is concentrated in the Office du Niger area near the existing sugar factories Sukala and Nsukala. Alcohol is also produced by these sugar refineries, which produce 11 million litres of ethanol per year. This production is mainly intended for industrial and pharmacy purposes and export to neighbouring countries. The Sugar Company of Markala (SoSuMar) plans an annual production of 15 million litres of ethanol and 30 MW of electricity by cogeneration, of which a surplus of 3 MW will be transferred to the electricity network of the Société Énergie du Mali (EDM-SA). ANABED, the national agency for the development of biofuels, manages activities related to biofuel. Numerous projects for the production and use of bioethanol, biodiesel, or pure vegetable oil have been launched in recent years. As for Jatropha (jatropha), it was first cultivated as a traditional fence for agriculture and is mainly concentrated in Sikasso, Koulikoro, Kayes, and Ségou, with an estimated production area of 65,000 ha allowing for an annual production of 5,500 metric tonnes of Jatropha seeds in 2016. There are already four presses and a refinery operation in the country (740,000 litres of biofuel were made from jatropha in 2016 with an annual growth of 35% since 2010) *(SE4ALL., 2019)*. Many pilot projects for the production and use of crude oil from jatropha (Jatropha) have been implanted, mainly in multifunctional and generating electricity units that can use crude jatropha oil in place of conventional diesel. The area of jatropha was estimated at 2000 ha in 2014. A standard defining the oil characteristics of pure jatropha plants for use in diesel engines, stationary and mobile, was made available. The transformation into biodiesel was carried out by a private biodiesel production unit in Koulikoro with a capacity of 2000 litres per day *(Fronteras., 2016; IRENA., 2019).*

9. Rural Electrification

Solar energy has been a very important resource for rural electrification in Mali. Hybrid systems (solar, diesel) and mini hybrids (solar and diesel) are currently one of the major components in rural electrification strategies. Solar technologies and kits are used in rural areas in schools, health centres, street lighting for public places, solar refrigerators and water heaters, solar pumping systems, solar mills, and solar dryers to improve access to modern energy services, improve livelihood conditions, and induce women's empowerment through income-generating activities through these decentralized energy services. Approximately 10% of rural energy services are RES (renewable energy services), mainly small-scale applications such as solar home systems (SHS) and hybrid systems *(African Development Bank Group & Green Mini-grid Market Development, 2018).* Private energy companies and local initiatives are the drivers of these rural electrification programs under the control of AMADER *(AfDB., 2015).* It considers small localities not served by the existing and planned electrical networks *(Bromand et al., 2012).* Two different approaches have been used for that: first, concessions. For this approach, rural electrification projects are awarded to private operators selected through a call for tenders. And last are the applications, also called “unsolicited application projects," whereby private operators send electrification proposals for a smaller locality or a specific group of localities. Later, in 2010, it enabled the electrification of 111 small localities (32,000 customers in total) *(Amader., 2011; Nygaard et al., 2012)*. Solar energy and other renewable energy sources are gradually replacing fossil resources in the form of off-grid area electrification; the country already accounts for more than 200 min-grid connected and isolated mini-grids installed. Mali is targeting a goal of 61% rural access by 2033 to be achieved through new strategies such as improving the efficiency of the installations, renewable energies, and jatropha’s oil.

The following are some successful projects and programs in the sector of rural electrification that were conducted with support from several international:

Solar Energy Village Lighting Project (PEVES, total), funded by India and the national budget, PEVES I 2003-2007 (1830 lighting kits, 6 refrigerators, 120 street lamps, 20 portable lamp systems, 12 solar pumps, 12 kits for rural television centres, 12 kits for rural telephone sets), PEVES II 2009-2013 (180 solar pumping systems, 2700 lighting kits, 461 portable lamp systems), and PEVES III 2014-2018 (15,000 photovoltaic solar kits, 40 photovoltaic solar pumps for the provision of drinking water, 1,000 portable lamps per village, 1,000 solar street lights).

The Municipal Electrification Project (phase I 2006–2009 focused on the electrification of municipal services, and phase II 2009–2017 focused on individual systems) was funded by GIZ and executed by AMADER. Domestic Energy and Access to Basic Services in Rural Areas Project (PEDASB-HEURA, Domestic Energy and Universal Rural Access, 2003-2013)

News and Renewables for the Advancement of Women (PENRAF, 2004–2012, founded by UNDP and the national budget), operated by CNESOLER (now AER); intervention in the 312 villages of Koulikoro, Ségou, Sikasso, and Mopti; creation of the solar village of Sirakorola. Regional Solar Programme II (2003–2008, solar pumping, 73 million euros for the countries of the Interstate Committee for Drought Control in the Sahel, CILSS, supported by the European Union), executed by CILSS.

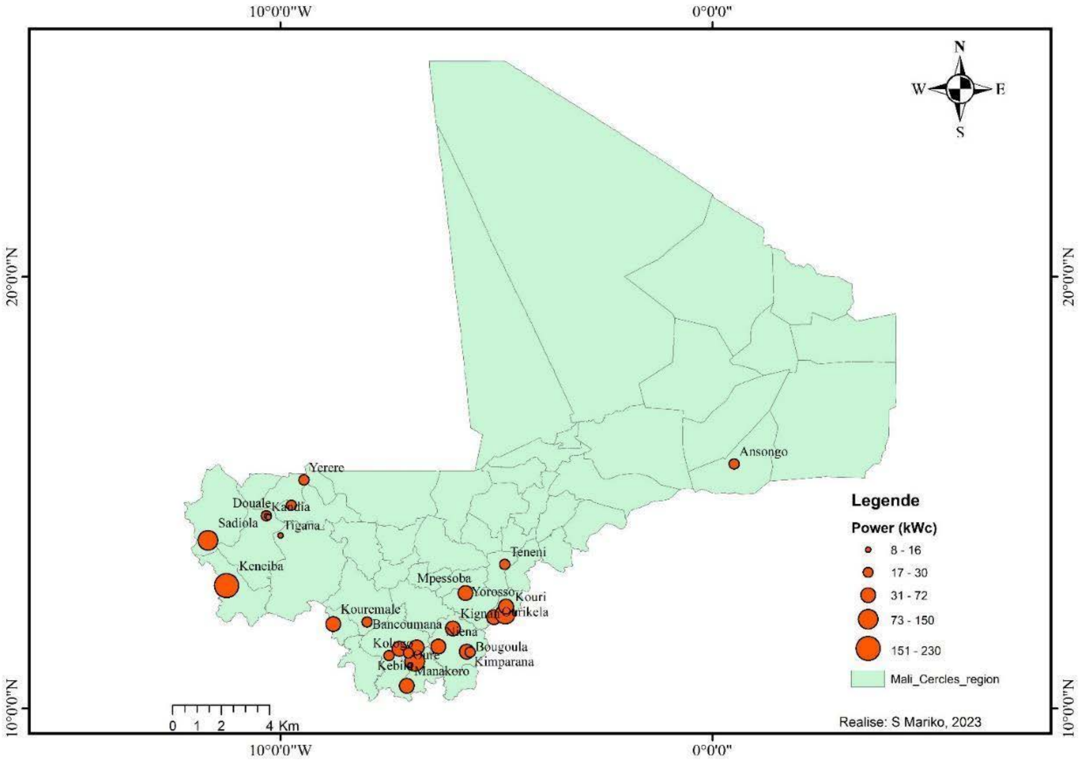


Figure 15: isolated mini-grid system installed for rural electrification (data from EDM)

10. Domestic energy:

Domestic energy use is estimated at 5 million tonnes per year, representing 400 000 ha of forest expected to exceed 7 million metric tonnes, or 560 000 ha *(IRENA., 2019)*.

Domestic energy refers to cooking energy consumption, primarily firewood (84%) with a low contribution of charcoal (14%). 96% of the energy is used in this sector is represented as follow: heat for cooking processes (54%), bathing and washing (20%), and space heating (17*%)* and this energy (fuelwood supply) come from the national forest reserve *(AfDB., 2015; MacCarty and Bryden., 2016).* Besides access to clean cooking energy and cooking technologies, the country Mali lies very far behind compared to other sub-region countries. To transition towards a cleaner domestic energy pattern and induce the restoration of the country's forests (which are decreasing under the weight of domestic energy consumption), the government intends to develop a modern cooking accessibility program (strengthening of clean, safe, sustainable, and affordable technologies), as well as promote technologies using alternative fuels to wood energy, especially LPG. The efficiency of the improved equipment is around 15%–33% of the objectives in Table 1 *(Rapport and Climatiques., 2018).* The use of cleaner and modern energy and improved stoves for cooking will also help improve environmental and health conditions and allow the women and girls principal actors involved in collecting fuel wood in rural and semi-rural areas to save time. It will also allow the country to move up towards achieving several sustainable development goals (SDGs), particularly goals 7 and 11 or 13. At the same time, there are multiple efforts from the private sector (Malian Agency for Renewable Energy (AER), SNV Mali, AMADER, and other partners) to increase access to clean energy equipment and clean energy in the country and to make available and accessible certified improved equipment *(Energypedia., 2022).* Table 4 represents the objectives for improving clean cooking access to be achieved by 2025.

Table 4: clean energy access target according to the strategies

Objectives for 2020	**Objectives for 2050**
34.3% of the population have access to gas Butane (LPG)	62.5% of the population have access to Butane gas (LPG)
44% of the population have access to clean cooking equipment (Improved stoves)	82% of the population have access to clean cooking equipment (improved stoves)

III. 3. Energy transition in Mali and its multidimensional transformative process

Emissions from the energy sector in 2012 showed that the residential sub-sector occupies the first place with 82.20% of the significant emissions of the sector due to the increased consumption of wood energy (wood fuel and charcoal), followed by the transport sub-sector with 12.25% of the sector's significant emissions due to the consumption of fossil fuels (petrol and diesel). The transformation sub-sector (energy industries), with 4.73% of sector emissions in 2012, ranks third due to the consumption of fossil fuels in the production of electricity *(Durable., 2017).* The high dependence on traditional fuels such as wood, fuel, and charcoal, as is the case in Mali, exerts huge pressure on the country's forest cover and environment and exacerbates climate change *(Denton., 2004*). Several policy documents have stated the necessity of the Malian energy systems' transition and diversification, and they have been acknowledged as a crucial step in lowering greenhouse gas emissions *(Durable., 2017; Rapport climatic., 2018).* The process of progressively switching from the primary energy production source to one that is cleaner, like renewable energy from fossil fuels, is referred to as an "energy transition*" (Hache., 2016).* In the shift in energy systems, renewable energy is crucial. As things stand, Mali's move towards renewable and sustainable energy systems has so far taken an ambiguous and imprecise turn. Therefore, Mali's energy transition should concentrate on renewable sources and be focused on the residential sector.

Mali has been concentrating on raising its renewable energy consumption percentage and reducing its reliance on fossil fuels by moving away from conventional biomass use and towards LPG *(Gazull et al., 2019).* Energy sustainability and security will be greatly enhanced by the addition of renewable energy resources to the Mali energy system. Prioritizing the removal of obstacles to solar and other local and renewable energy resources is necessary to guarantee Mali's transition to a resilient and sustainable energy system.

a. Energy Supply Diversification

The Malian energy sector’s vulnerability to climate change has been highlighted in the National Adaptation Programme of Action. Noticing the energy systems' dependence on hydrocarbons and natural resources (biomass), in addition to the government commitments in favour of renewable energies, a transition and diversification are necessary to provide an adequate response to growing energy needs and achieve the sustainability of the systems. Energy transition has a tremendous role to play in solving the current problems, and renewable energy is key to energy security, sustainable economic development, pollution, and climate change *(Fadly., 2019; Mercedes and Cantarero., 2020).* A radical transformation of energy systems is required to reduce greenhouse gas emissions and avoid the long-term consequences of global climate change. Energy transition to a low-carbon energy system can have many advantages for a developing nation like Mali; it brings environmental benefits (help mitigate and adapt to climate change impacts) or socio-economic advantages (bring light and help rural and remote communities in social activities like healthcare and others) and income-generating activities. Energy demand is out-taking energy supply in the country, and considering the country's dependence on fossil fuel imports, the cost instability of fossil fuels, its environmental burden, and the climate change impact on the hydro and biomass energy systems (the major share of the Malian energy supply), the unmet demand is set to be supplied through the use of renewable energy and decentralized systems for a sustainable, resilient, affordable, and reliable energy system. The construction of micro-dams and other water supply structures was listed as one of the eighteen priority activities in the National Adaptation Programme of Action (NAPA) in 2007 in climate change adaptation and migration *(Warner., 2018).* It seems like a great strategy to improve energy supply, but still, the diversification aspect was missing on the basis that the country's supply is predominantly based on hydropower. The rapport suggests that increasing green energy (renewable energy and local energy resources) access could be essential to climate change action (mitigation and adaptation) in Mali (African Development Bank Group & Green Mini-grid Market Development., 2018).

b. Policies and Action Supporting Energy Transition and Achieving Sustainable Energy Supply in Mali

Mali has energy policies and strategies in place to help mitigate and adapt to climate change and sustainably manage the country's already vulnerable energy systems. Through energy planning strategies and policy documents, the aim for future energy systems is to achieve strategic goals such as reliability, energy security, sustainability, affordability, efficiency, and environment-friendly technologies. Most of these targets need to be updated to the current circumstances *(African Development Bank Group & Green Mini-grid Market Development.,2018).* These regulations and policy documents support energy transition, energy efficiency and sustainability, renewable energy uptake in the energy mix, energy mix diversification, and climate change adaptation and mitigation. They are primordial in the fulfilment of the country’s Nationally Determined Contribution and an important step towards climate change adaptation and mitigation. The following represent key energy policies and legislative and regulatory texts.

c. National government strategies and policies

In 2011, the Malian Ministry of Environment and Sanitation launched its National Climate Change Strategy (NCCS), a strategy that was developed with the main objective of facing climate change challenges and ensuring sustainable development in the country. The strategy works towards the year 2025 by evaluating the progress made every 5 years to revise the eight axes of which the strategies consist, including the implementation of a national institutional framework on climate change, organization of access to international climate funds, national capacity building, and stimulation of climate change consideration within activities in different sectors and at all administrative levels. Numerous action plans and policy documents have been formulated by the Government of Mali all in the sense of sustainable energy supply, natural resources management and climate adaptation and mitigation. The National Policy for Climate Adaptation, Climate Change Scenario Elaboration, Sub-Regional Action Programme for the Reduction of the Vulnerability to Climate Change, as well as its Initial National Communication (2000) and Second National Communication (SNC) (2012), which have been submitted to the UNFCCC and are currently under implementation. Mali ratified the UN Convention on Biological Diversity (CBD) in 1995, for which it had a National Biodiversity Strategy and Action Plan approved in 2015; the Convention to Combat Desertification (CCD) in 1995, for which it developed a National Action Programme in 1998; and the United Nation Framework Convention on Climate Change (UNFCCC) in 1994. Mali signed the Paris Agreement for Climate Change in April 2016 and ratified the agreement in September 2016, with it entering into force in November 2016. Mali developed a National Adaptation Programme of Action (NAPA) in 2007. Other strategies and policy documents elaborating the future pathways of Malian energy include the following: National Energy Policy: National Strategy for the Development of Renewables, National Strategy for the Development of Biofuels, National Strategy for the Development of Biofuels, National Strategy for the Utilisation of Energy, etc.

III. 4. Conclusion

Besides significant achievement, the system relies still very much on fossil fuel and traditional biomass. The population still relies strongly on traditional solid biomass (fuel wood, charcoal, animal waste, and so on) for cooking and heating needs, Access to modern clean cooking energy rate at the national level is still as low as 1% *(IRENA., 2019)*. Increasing the sustainability level of the current system, considering the greenhouse gas emissions, deforestation (particularly in the Sahelian context of Mali), land use changes, environmental and health impacts, and climate change are harmful to the population and the environment is now more than every urgent. A sustainable energy system for Mali must consider modern renewable energy resources, energy efficiency, and climate change adaptation and mitigation frameworks in the different policies and strategies documents. Sustainable energy (clean, affordable, and reliable modern energy services such as electricity and non-solid fuels) in Mali can allow the country to meet several goals including the united nation sustainable development goals and the Paris agreements simultaneously (*Mercedes and Cantarero., 2020; Fadly.; 2019).* And more importantly, help toward the achievement of the NDCs. Additionally, international collaborations and investments are crucial in supporting Mali's transition to a more sustainable energy system.

Chapter IV: Methodologies

IV.1. Introduction

This section of the study will consider the different methodologies to best achieve sustainable energy planning considering sustainability dimensions: (environmental, technical, social, and economic) and the projection of the impacts of climate change on energy resources. The study area considers the West African region with focus on Mali (Latitude: 17° 34' 26.16" N Longitude: -3° 59' 9.99" W). The mean temperature is between 27°C and 30°C, which is increasing by the year. The rainy season in Mali is located between June and September, and during this period, the country receives more than 500 mm of rainfall *(Coulibaly., 2021)*. The methodological framework of the work is presented on figure16

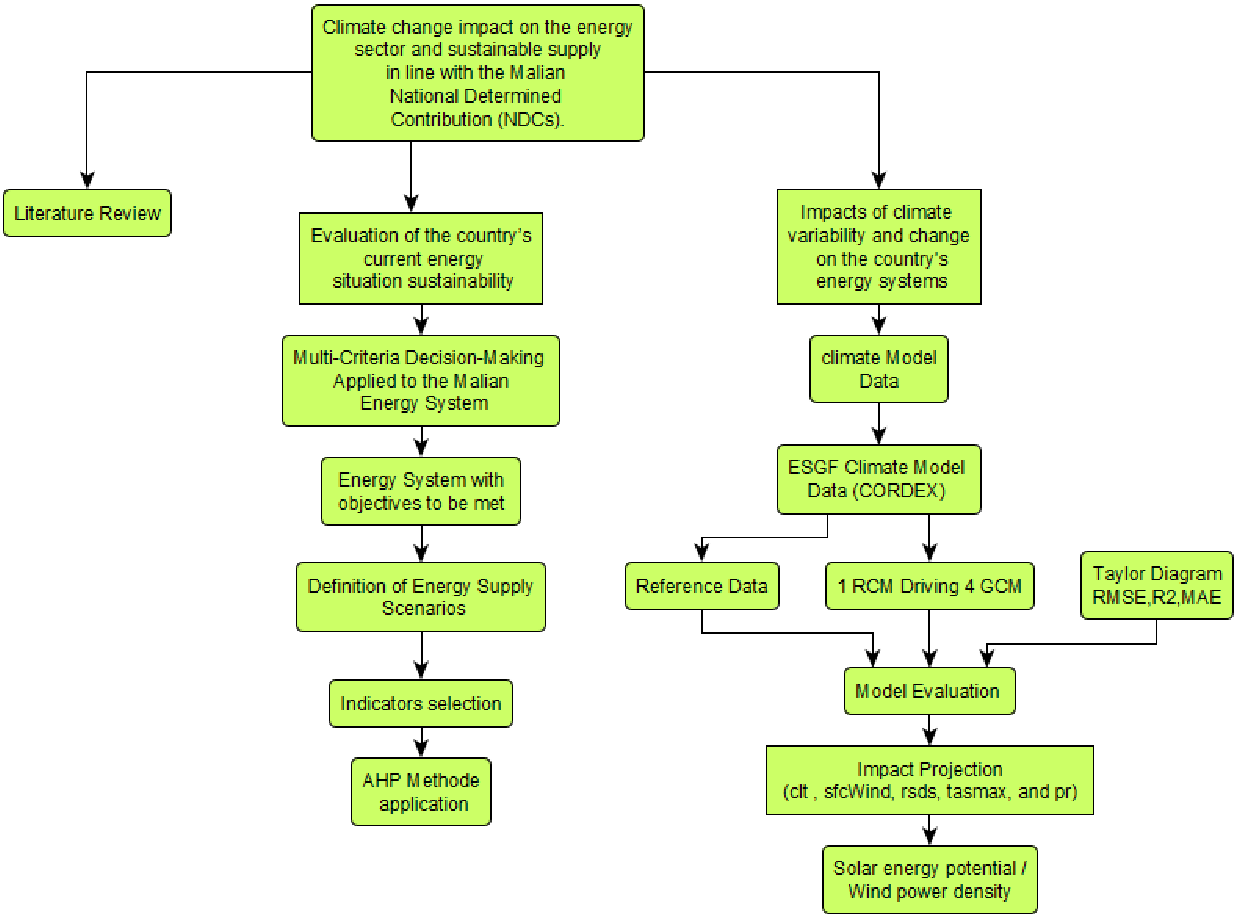


Figure 16: methodological framework

IV.2. Data and Data Collection Process

1. Data collection

To apply the multi-criteria decision-making approach, a survey was designed to identify the different dimensions and indicators for the country's energy sustainability evaluation. Brainstorming was done to identify the various stakeholders involved in the study, key groups in the electricity generation and supply sector: individuals involved in general electricity governing and supply (different energy agencies energy companies and NGOs intervening in the energy sector), academics who had authored energy/climate change papers and energy service users. The sampling approach is called purposive sampling *(Owei., 2017)*. Purposive Sampling is defined sampling approach that involves a non-random, strategic sampling of individuals that are relevant to the research questions whilst maintaining variety in the *sample (Owei., 2017).* The semi-structured interviews allowed us to collect energy and socioeconomic data on energy resource production next to the various energy agencies in the country and to determine the evaluation criteria to be used in the application of MCDM and prioritize the different dimensions. Twenty (20) indicators based on four (4) sustainability dimensions were selected in *Table 10*. Data availability has been a major factor in this selection the aspirations and strategies towards the socio-economic development of Mali. The questionnaire (see appendice1) was submitted to key energy institution actors and other energy stakeholders and the responses of 80 respondents *(Table 5)* were used to prioritize the dimension and criteria. We employed both quantitative and qualitative data to estimate the most dimension (technical, social, economic, and environmental) indicator values.

Table 5: National Institutions Involved in the Survey and the Number of Respondents

National Institutions Involved in the Survey		**Number of Respondents**
DNE	The national direction of energy	6
AMADER	Malian Agency Domestic and Rural Energy	10
AER	Agency for Renewable Energy	6
ANADEB	National Agency for Biofuel Development	2
GIZ MALI	German Society for International Cooperation	5
EDM-SA	Malian Electricity Company	30
ACCESS	Private Company for rural electrification	1
USTTB	The University of Science, Technique, and Technology	20
TOTAL		**80**

2. Data sources

The following data was used in assessing climate impact on energy supply sustainability and the Malian NDCs effectiveness.

Table 6: data and data source

Data Type	Variable	Periods	Sources
General Energy Data	Consumption by Sector, Production by Sector National Energy Policies and Plans, Annual Statistical Reports (Energy), Energy and GHG Mitigation, GHG Inventories, Local Emissions Factor	1980 - 2020	
Electric Sector Data	Current And Historical Installed Capacities (MW), Efficiencies (Losses), Costs, Capacity Expansion Plans, Transmission, Distribution, Losses, CHP Production Data, Rural Electrification Rates, Rural Electrification Expansion Plans,	1980 - 2020	SIE/EDM/ AMADER
Renewable Energy Data	Installed Capacities, Efficiencies, Costs, Expansion Plans, GHG Mitigation Assessments	1980 - 2020	ANADEB/ AER/
Socio-Economic Data	National Population Data, Rates of Urbanization, Average Household Size, Population by Region, GDP/GNP Data, Value Added by Sector, Interest Rates, Inflation Rates Employment Statistics, Investment/National Savings Rate	1980 -2020	INSTAT
Climate Data	Temperature, Wind, Precipitation Humidity, Evaporation,	1980 -2020	Met Service

3. Climate parameters and Model choice

The variables clt (total cloud fraction), sfcWind (near-surface wind speed), rsds (surface downwelling shortwave radiation), hurs (near-surface relative humidity), tasmax (daily maximum near-surface air temperature), and pr (precipitation) evolution have a significant impact on the evaluation of renewable energy resources. The spatial resolution of these simulations is 0.44° × 0.44°, or about 50 km over the African domain. For the relevant variables (described in the below subsections) were retrieved for the four (4) different climate models and the observation ERA-INT: ECMWF-ERAINT, MIROC-MIROC5, NCC-NorESM1-M, CCCma-CanESM2 and MOHC-HadGEM2-ES.

Table 7: long name of the selected variables

Variable NA-CORDEX. (n.d.)	**Unites**
clt (Total Cloud Fraction)	%
sfcWind (Near-Surface Wind Speed)	m/ s
rsds (Surface Downwelling Shortwave Radiation)	W /m^2
hurs Near-Surface Relative Humidity	%
Tasmax (Daily Maximum Near-Surface Air Temperature)	K
pr (Precipitation)	Kg/m^2 s

The model simulations used are the Coordinated Regional Climate Downscaling Experiment (CORDEX), with a spatial resolution of roughly 50km (0.44° x 0.44°). From the CORDEX datasets, daily clt (total cloud fraction), sfcWind (near-surface wind speed), rsds (surface downwelling shortwave radiation), hurs (near-surface relative humidity), tasmax (daily maximum near-surface air temperature), and pr (precipitation). Four (4) GCMs are selected for this study plus ECMWF-ERAINT reanalysis, downscaled from the Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model (RCP4.5 and RCP8.5). The outputs from these two scenarios (2006–2100) from the following GCMs (ECMWF-ERAINT, MIROC-MIROC5, NCC-NorESM1-M, CCCma-CanESM2, and HADGCEM) are used, and historical data (1981–2005) is downloaded from the Earth System Grid Federation (ESGF) *(CORDEX, n.d.)*. The details of the datasets used in this work are shown in Table 8. ERAINT-evaluation (1980–2010) for the evaluation of the climate model simulations (validation of the model for the present-day period). Data on the period 1980–2006 were used, on which both reanalysis datasets overlapped. The choice of the different model is motivated by their availability on several levels: on a daily time, step over a long period (>30 years) for the parameters and the climate scenarios RCPs 4.5 and 8.5, and observation data are obtained from the Earth System Grid Federation (ESGF) website *(CORDEX, n.d.),* namely SMHI.ECMWF-ERAINT, lastly for their increasing use in west African research and accruing to previous studies *(Warnatzsch and Reay., 2019; Ashaley et al., 2020; Sawadogo et al., 2021b; Sawadogo et al., 2019; Sawadogo et al., 2020).*

Table 8: CORDEX-RCMs and their driving GCMs

CORDEX-RCM and driving GCMs			
Datasets	**Institution**	**RMC**	**Reference**
ECMWF-ERAINT	Swedish meteorological and hydrological institute (SMHI)	RCA4	*(Sawadogo et al., 2020)* *See: (Warnatzsch and Reay., 2019)*
MIROC-MIROC5			
NCC-NorESM1-M			
CCCma-CanESM2			
MOHC-HadGEM2-ES			

IV.3. Evaluation of the country’s current energy situation sustainability

1. Definition of Energy Supply Scenarios for Mali

To evaluate the energy situation in Mali, scenarios are considered. The development of these scenarios consisted of two stages: first a literature review and second energy expansion plans based on Mali national energy policies. Six (6) different energy supply options (scenarios) for Mali at the horizon of 2050 were defined. The assumptions considered the overall objective of the National Energy Policy (PEN) which has been lightened in the energy situation of the country stated above. Future energy planning that may or may not happen and provide answers to ‘what if’ types of questions is assessed using scenario analysis to assess alternative Malian energy futures and assess the sustainability implications. The scenario definitions consider different factors, including policy and socio-economic drivers such as economic growth, security of supply, and mitigation of climate change as well as the anticipated technological development in the future *(Santoyo-Castelazo and Azapagic., 2014)*. The period of analysis covers the period from 2020 to 2050. The scenarios reflect the aspirations of the Malian government to transform the country’s energy systems: increasing energy efficiency, increasing the share of renewable and decreasing the dependency on traditional biomass *(PANEE., 2015; PANER., 2015; SE4ALL., 2019)*. The perspective of oil and Hydrogen exploitations and nuclear energy are foreseen by the report, but the present study considers these options unsustainable considering that Mali doesn’t have the technological expertise in place, the study considers that this field will be socially and economically burdens to be integrated into the national energy supply. The (6) scenarios focus on the targeted domain of intervention depicted in the national policy documents and energy strategies:

- Reducing the consumption of biomass used for cooking, through the wider dissemination of efficient improved stoves.
- Development of renewable energies

- Improving access to electricity and efficiency in the supply

Scenario 0: BAU

This scenario assumes no significant changes in the current energy trends. The heavy reliance on biomass (74%) and fossil fuel importation (22%) is assumed to continues, with minimal electricity production (4%). This scenario projected without necessary correction to meet SGDs as it is.

Scenario 1: increases the share of renewable energy and reduction of the share of traditional biomass

Focuses on decreasing the consumption of traditional biomass and increasing the share of renewable energy. It includes the introduction of modern biomass (briquettes) and aims to improve electrification rates. Hydropower is assumed to remain the main source of electricity, supplemented by thermal and solar energy.

Scenario 2: increases the share of renewable energy and reduction of the import

It Aims to diversify electricity supply and reduce reliance on traditional biomass and imports. This scenario promotes the use of modern biomass (efficient charcoal production) and increases the share of renewable energy sources like solar and wind.

Scenario 3: increases the share of electricity access and energy diversification

Emphasizes the deployment of renewable energy resources and reducing dependence on hydropower. It aims to diversify energy sources, including solar, wind, and bioenergy, to improve electricity access and system reliability.

Scenario 4: decrease CO_2 emission, prioritising renewable in the energy mix.

Focuses on decarbonizing the energy system by increasing the share of renewable energy in the mix. It aims to make the most use of local resources, introduce energy efficiency measures, and minimize losses in energy production, transmission, distribution, and consumption.

Scenario 5: increase the electricity importation

Relies on importing a significant share of electricity through interconnectors with neighboring countries. This scenario leverages the advantage of hydropower and aims to increase national electricity access through imports.

To make all the options comparable, the assumptions in scenario 0: BAU of the annual energy demand growth rate of 10% increase *(AfDB., 2015)* was assumed to be constant on the period of analysis. As shown in Figure 20, the scenarios adopt an increase or decrease in the proportion of production sources between 2020 and 2050. The percentage of the technology is dependent on the nature of the scenario. The corresponding energy mix then prioritises the production sources that the scenario represents.

Table 9: Detailed Scenario of energy supply in Mali to 2050

S0	Scenario 0: BAU	The current energy trend is based on the heavy reliance on biomass (fuel wood and charcoal) 74% and the dependence on fossil fuel importation 22%; with a small share of electricity production 4%, biomass74%, petroleum products 22%, hydro 50.7%, solar 2.4%, wind 0%, thermal 46.9%, import 17% of electricity.	The business-as-usual (BAU), where no action is taken, and the current energy situation is projected to be the same by 2050. This is the basic scenario, in which current trends persist without the necessary corrections to meet the SDGs.
S1	Scenario 1: increases the share of renewable energy and reduction of the share of traditional biomass	Energy policy supporting development strategies that support the decrease of energy consumption pressure on the forest reserves by decreeing the share of traditional biomass in the energy mix: electricity 17%, biomass 50%, modern biomass10%, petroleum product 23%, hydro 20%, solar 28%, %wind 2%thermal 30%, import 17%, bioenergy 3%	Scenario 1 assumes a slow and steady transition from this resource to introduced modern biomass in the form of briquettes, which denotes the reduced access to energy supply and the low level of electrification in the country. Hydropower is the main source of electricity generation followed by thermal production together with minor contributions from miner share producers from solar energy.

S2	Scenario 2: increases the share of renewable energy and reduction of the import	Energy policy supports diversification of electricity supply and encourages investment in low-carbon options with emphasis on renewable energies. Favour strategy that supports the increase of renewable energy share in the mix energy: electricity 17%, biomass 40%, modern Biomass 20% natural gas 3%, petroleum products 20%, hydropower 30%, solar 30 %, wind 10%, thermal 15%, import 0% of electricity, bioenergy 15%.	This option proposes to steadily decrease the use of traditional biomass and introduce the modern biomass (charcoal produced by efficient carbonization). Increase the production of electricity to improve the rate of electricity access and diversify the production resources to increase renewable energy sources in the generation and induce reliability of the systems.
S3	Scenario 3: increases the share of electricity access and energy diversification	An energy development strategy that supports the deployment and energy diversification of renewable energy: electricity 40, biomass 27%, modern biomass 10%, natural gas 3%, petroleum product 20%, hydro 25%, solar 30 %, wind 10%, thermal 15%, import 5%, bioenergy 15%	This scenario focuses on the deployment of renewable energy resources. It takes account of all renewable energy resources available in the country and highlights the reduction of the country's dependence on hydropower production.
S4	Scenario 4: decrease CO_2 emission, prioritising	An energy development strategy that supports the decarbonization of the energy systems and the adaptation and mitigation of climate change: electricity 70%, biomass 10%, modern biomass 5%, natural gas 5%, petroleum product 10%, hydro 25%,	This scenario focuses on making the most use of local resources to meet long-term demand, diversification of energy supplies, finding new and renewable energy sources, introducing energy efficiency measures, and minimising

	renewable in the energy mix.	solar 35%, wind 10%, thermal 0%, import 5% of electricity, bioenergy 25%	losses in energy production, transmission, distribution, and consumption.
S5	Scenario 5: increase the electricity importation	Energy development strategy, the increase electricity access at the national level and with strong support for electricity import from Neighbouring countries: electricity 70%, biomass 10% modern biomass 5%, natural gas 5%, petroleum product 10%, hydro 18.4%, solar 22%, wind 0%thermal 38.1, import, 41.3% of electricity, bioenergy 0%,	Scenario 5 focuses on the dependence of the country on hydropower as well as the advantage of the interconnectors between the countries for electricity sharing by importing a significant share of its electricity through these systems.

2. Multi-Criteria Decision-Making Applied to the Malian Energy System

To propose a sustainable energy system considering the country's (Mali) energy policies and development plans, a Multi-Criteria Decision-making approach was applied. Twenty (20) indicators based on four (4) sustainability dimensions were selected after extensive literature reviews to be the base of the systems assessment. Data availability has been the major factor in this selection. Indicators are strongly dependent on the type of system they monitor. The selection of indicators has prioritised aspirations and strategies towards the socio-economic development of Mali, where income creation is identified as the most important aspect hence the choice of consideration.

Table 10: List of evaluation criteria for Malian energy supply

Dimensions	Indicators	Unit	Nature	
Technical	TCH1: Production Efficiency	(%)	Positive	*(IAEA, 2007)* *(EIA, 2021)* *(Fang et al., 2018)* *(Wang et al., 2009)* *(Stein., 2013)* *(Brand and Missaoui., 2014)* *(Banacloche et al., 2020)* *(Siksnelyte-Butkiene et al., 2020)*
	TCH2: Capacity Factor	(%)	Positive	
	TCH3: Resources potential	(MW)	Positive	
	TCH4: Reliability of the system	Qualitative	Positive	
	TCH5: Resources availability	(Toe)	Positive	
Economical	ECO1: net import dependency	(%)	Negative	
	ECO2: Fuel cost	$ / MMBtu	Negative	
	ECO3: Levelized cost of electricity	$/ kWh	Negative	
	ECO4: Investment cost	$/kW	Negative	
	ECO5: Payback period.	years	Negative	
	ECO6: Government support	Qualitative	positive	
Social	SCO1: Energy acceptability	Qualitative	Positive	
	SCO2: Energy accessibility	Qualitative	Positive	
	SCO3: Job creation	prs. /MW	Positive	
	SCO4: energy Affordability	Qualitative	Positive	
	SCO5: People displacement	Qualitative	Negative	
Environment	ENV1: Energy diversification	%	Positive	
	ENV2: Fraction of renewable energy	%	Positive	
	ENV3: Land demand/ Rate of deforestation	m2/MWh/ km2	Negative	
	ENV4: Emission and Global Warming Potential	gCO2e/kWh	Negative	

a. Indicator Descriptions

Table 11: Indicator Descriptions

Indicator	Definition/Description	Measuring method
TCH1: Production Efficiency	Efficiency of energy conversion and distribution, including fossil fuel efficiency for electricity generation, efficiency of oil refining and losses occurring during electricity transmission and distribution, and gas transportation and distribution	The energy conversion efficiency is the useful energy output (benefit) divided by the energy input (cost)
TCH2: Capacity Factor	Capacity factor is the measure of how often a power plant runs for a specific period of time. It's expressed as a percentage and calculated by dividing the actual unit electricity output by the maximum possible output. This ratio is important because it indicates how fully a unit's capacity is used	Ratio the actual electrical energy output over a given period of time to the maximum possible electrical energy output over that period
TCH3: Resources potential	The resources potential of a country represents how much energy the country gets from coal, oil or gas, solar or wind. It allows the country to check how much energy is available to go in its energy mix	Sum (potential coal (toe), potential gas (toe), potential oil (toe), potential solar (toe), potential wind (toe))
TCH4: Reliability of the system	Reflects whether the energy supply is subject to interruptions. It could be to power rationing like the case happens in the country when the power production isn't enough the satisfy the demand Reliability is the ability of a power system to deliver energy in the quantity and with the frequency required and is represented by the loss of power supply	The number and hour of power shortages due to in power insufficiency and the per capita energy use

	probability (LPSP) knowing almost 90% of failures occur in the distribution systems.	
TCH5: Resources availability	Refers to the availability of the local resources, measured as the potential resource production on site. For renewable sources, the production is taken only on useful area (e.g., the solar area was considered only when a certain percentage of population was within the area with potential solar radiation.	Biomass potential (agricultures waste, urban waste, energy crops...)
ECO1: net import dependency	The dependency rate shows the extent to which a country relies upon imports in order to meet its energy needs, it is the ratio of net import to total primary energy supply (TPES) in a given year in total and by fuel type	Total primary energy supply (TPES) national production divided by the total amount imported / total imported by the percentage of energy use
ECO2: Fuel cost	the cost of fuel for energy production	Cost of energy production
ECO3: Levelized cost of electricity	It measures the average cost of producing electricity over the supply chain of the system. This indicator was calculated with local data and using the LCOE formula and information regarding to O&M, investment cost and energy production through lifetime	The indicator values have been taken in literature
ECO4: Investment cost	Total cost of investment for energy production	Sum of investment cost of individual energy production technology

ECO5: Payback period	The period or amount of time an energy production system will have repaid for it cost	It is determined by comparing the cost of the initial investment with the annual returns
ECO6: Government support	The government support for the population to usually afford energy cost/ Subside are measures that keep prices for customers below market levels, or for suppliers above market levels, or reduce costs for customers and suppliers. Energy subsidies may be direct cash transfers to suppliers, customers, or related bodies, as well as indirect support mechanisms, such as tax exemptions and rebates, price controls, trade restrictions, and limits on market access.	Production cost/ supply cost
SCO1: Energy acceptability	Reflects the attitude of the population towards the use of certain type or other type of energy or fuel	The indicator has been measured qualitatively on the scale of (L: low, H: high, to VH: very high) according to population preference which could also be replace by number from (1-5)
SCO2: Energy accessibility	Defines energy access as "a household having reliable and affordable access to both clean cooking facilities and to electricity, which is enough to supply a basic bundle of energy services.	The share of the population that have access to energy

SCO3: Job creation	The construction, operation, maintenance capacity expansion contributes to the creations, the job creation account for the job creation of individual technologies job creation applied to the installed or the to be installed capacity of the technologies	Number of paid hours per kWh produced in lifetime (hours/kWh)
SCO4: energy Affordability	The capability of the population the afford energy in the country the percentage of household income spent on energy bills	Domestic fuel price fluctuation ratio, Crude oil price fluctuation ratio, GDP per capita
SCO5: People displacement	Relates to side effects caused by the construction and operation of the power plant on surrounding communities, considering relocation of inhabitants, due to factors related to risks, proximity to resource source area or power plant.	
ENV1: Energy diversification	Number of respective entities per kWh produced in lifetime (Number/kWh)	Number and share of commodity (crude oil, coal and natural gas) in the energy mix
ENV2: Fraction of renewable energy	The renewable fraction is the fraction of the energy delivered to the load that originated from renewable power sources.	(Total production - the renewabLe energy production)/100

ENV3: Land demand/ Rate of deforestation	The land required to produce a given quantity for an energy technology and in the case of cooking energy Annual change in the amount of natural and forest area tracked over time that could be attributed to using wood as a fuel for energy purposes and areas for news energy capacities	total land cover/ total installed capacity
ENV4: Emission and Global Warming Potential	GHG emissions, expressed in tones of CO2-equivalence per kWh generated, during the entire supply chain of the energy systems, including processes before electricity generation, e.g., mining, plant construction, transportation among other activities that are considered within the scope of electricity generation.	Individual greenhouse gas emission per unit of energy production and it GW potential

b. *AHP Method*

This study applied AHP to a three-step steps approach, problem decomposition, pairwise comparison, and synthesising as done by *Bhandari et al., (2021)* to rank the different alternatives. The data were aggregated into a decision matrix. The principle is to compare different alternatives by identifying a set of evaluation criteria applicable to all the alternatives. The values of these criteria are then normalised, and their weights are determined according to the relative importance of the criteria *(Wang et al., 2009).*

Step 1: Decomposing the problem

The following flowchart (*Figure 17*) depicts the Decomposing problem considered in the energy situation of Mali.

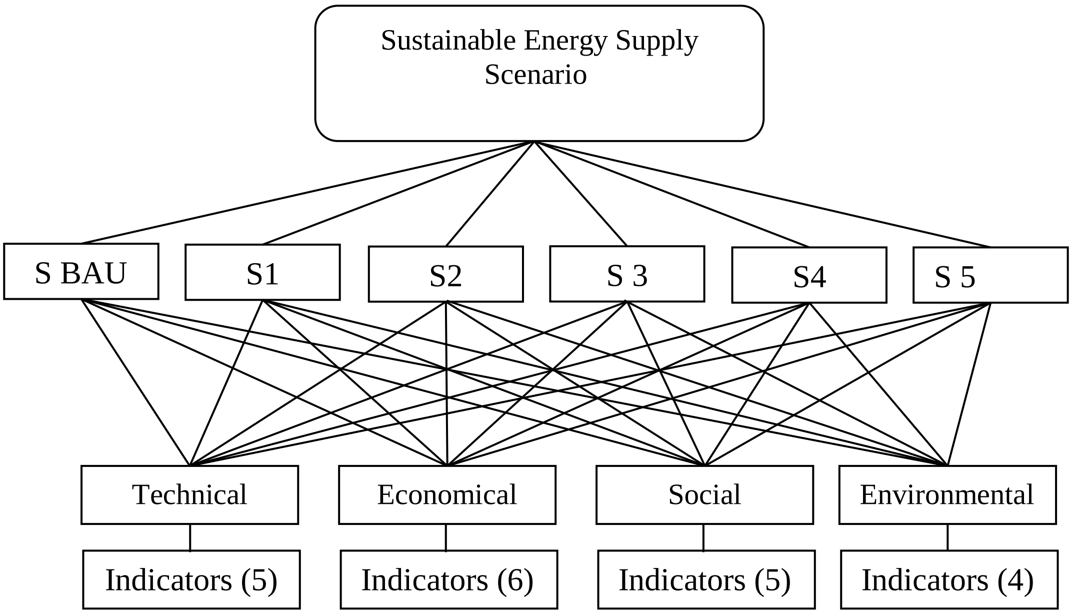


Figure 17 : Dimensions and indicator numbers (adapted from Bhandari et al., 2021)

Step 2: Pairwise comparisons

Weights and ranks of selected criteria are determined by pairwise comparison. The sub-criteria are compared concerning the corresponding main dimension, and the different scenarios are compared with respect to each sub-criterion to determine the weights and rank the different sub-criteria and alternatives *(Mastrocinque et al., 2020).* During this step, the pairwise comparisons are organised into an n * n matrix.

Assumptions and data sources

All the initial indicator values for individual technology were taken from the literature *(Bhandari et al., 2021; Diakoulaki and Karangelis., 2007; Stein., 2013; Troldborg et al., 2014).* The initial indicator values per scenario are obtained from processing the following formula. The obtained values are then considered as the initial indicator values per scenario.

$$X_{ij}X_{ij} = \frac{\sum Id_i * Perc\ Id_{ij}}{\sum_i^n Perc\ Id_{ij}} \qquad \textit{Equation 1}$$

$i: scenario,\ j: indicator,\ X_{ij}$: initial value of the indicator per scenario, $Pert\ Id_{ij}$: percentage per the scenario, Id_{ij}: initial value of the indicator.

Normalization

To evaluate the equivalence, the indicators have to be brought to a common scale through normalization. By normalization, a direct comparison is achieved because each indicator is dimensionless, with values between 0 and 1. The normalization processes were achieved through linear normalization *(Vafaei et al., 2016)* as follows:

Normalization equation of positive-type indicators (beneficial criteria):

$$\underline{X_{ij}} = \frac{X_{ij}}{X_j Max} \qquad \textit{Equation 2}$$

Normalization equation of negative-type indicators (non-beneficial criteria)

$$\underline{X_{ij}} = 1 - \frac{X_{ij}}{X_j Max} \qquad \textit{Equation 3}$$

$\underline{X_{ij}}$: the normalized value of the indicator, X_{ij}: initial indicator value

Step 3: Synthesis

To ensure the statistical consistency of the pairwise comparison, the consistency ratio needs to be calculated *(Bhandari et al., 2021)* in which the value should be less than 0.10 to show a statistical consistency (for consistency ratio for N greater than 15) *(Alonso and Lamata., 2006).*

IV.4. Evaluation of the impacts of climate variability and change on the country's energy systems

The study will evaluate projected changes and variabilities of the climate on energy resources such as precipitation, wind speed, and biomass potential in Mali under various global warming levels. Changes in the annual production of these energy systems will be evaluated as a function of resource availability. The impact of climate change and variability on existing solar energy systems and wind power density will be assessed. Three types of datasets will be analysed in this study: station observation, reanalysis, and climate model simulation datasets. The study will use EraINT reanalysis data at 0.44° × 0.44° resolution to assess the spatio-temporal variability of temperature and precipitation over Mali from 1980 to the present. The CORDEX resolution climate simulations will be used to assess the changes in future temperature and precipitation under various Representative Concentration Pathways (RCPs) 4.5 and 8.5.

IV.5. Method

Firstly, interviews involving Malian energy actors and institutions and literature reviews were used to define the sustainability of the current energy supply situation in Mali. In the previous chapters, we looked at the Malian energy system in depth. The present section will use that as a reference to look at the impact of climate change on the system as well as climate projections from the Coordinated Regional Climate Downscaling Experiment (CORDEX) project. The future energy supply changes will be investigated for the periods 2021–2060 and 2061–2100 in accordance with the nationally determined contribution of Mali, and using Regional Climate Model simulations of the CORDEX initiative based on two emission scenarios (Representative Concentration Pathways RCP4.5 and RCP8.5), the model projections will be compared with observation data.

The outputs of RCP4.5 and RCP8.5 scenarios (2006–2100) from the following GCMs: CCCma-CanESM2, MOHC-HadGEM2-ES, MIROC-MIROC5, and NCC-NorESM1-M are used, including the historical data ECMWF-ERAINT (1981–2005) downloaded from the Earth System Grid Federation (ESGF). Concentration Pathways (RCPs) 4.5 and 8.5 with the ERA-Interim reanalysis were accessed for four global climate models and for seven energy-related variables from the Coupled Model Intercomparison Project Phase 5 (CMIP5). Climate models and GHG emission scenarios both play a role in the projection of meteorological conditions *(Oka et al., 2020).* The choice of the different climate simulations was motivated by their increasing use in West African research and their capability to reproduce relatively well the climatology of the West African region according to previous studies *(Ashley et al., 2020; Gyamfi et al., 2021; Sawadogo et al., 2019; 2020; 2021; Warnatzsch and Reay., 2019).* The model simulations used are from the Coordinated Regional Climate Downscaling Experiment (CORDEX) with a spatial resolution of roughly 50km (0.44° x 0.44°), and the daily climate-related variables clt (total cloud fraction), sfcWind (near-surface wind speed), rsds (surface downwelling shortwave radiation), hurs (near-surface relative humidity), tasmax (daily maximum near-surface air temperature), and pr (precipitation) are used because of their direct impact on renewable energy resources' availability and generation. The details of the datasets used in this work are shown in Table 1. ERAINT-evaluation (1980–2010) is used for the evaluation of the climate model simulations (validation of the model for the present-day period). Data on the period of 1980–2006 were used, where both reanalysis datasets overlapped.

1. Methods of Analysis

We started the study by assessing the selected GCMs' skill in reproducing the historical climate over the country by validating the historical simulation against the observation dataset in terms of regional-specific climatic variables. Secondly, the future climate will be projected through dynamical downscaling under different representative concentration pathways (RCP4.5 and RCP8.5). Thirdly, we then evaluate the impact of climate change on the main power renewable sources including hydropower, wind energy, and solar energy, from a future energy planning perspective. Hydropower, solar energy, and wind energy are investigated by examining the resource availability related to precipitation, cloud cover, and wind speed changes. Lastly, the changes in future energy capacity installation can be addressed based on the estimated results driven by the climate variables influencing the entire energy system spectrum. The projected changes are defined as the difference between the future and reference periods expressed as a percentage of reference values (all variables).

2. Model Validation Methods

To assess climate model outputs' accuracy and how well they can be trusted to represent a future climate; it is crucial to first examine the extent to which the GCM baseline simulations reproduce observed characteristics of the variables. Hence, historical climate model outputs of these variables are assessed. The statistical tools and measures considered to quantify the accuracy of the GCMs are the following: correlation coefficient (r), standardised deviations (r), root mean square error (RMSE), mean absolute error (MAE), and coefficient of determination (R2) were used to determine model performance.

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(O_i - P_i)^2}{n}} \qquad \textit{Equation 4}$$

$$\mathrm{R2} = \frac{\frac{1}{n}\sum_{n=1}^{n}(\boldsymbol{O}_{i}-\bar{\boldsymbol{O}})(\boldsymbol{P}_{i}-\bar{\boldsymbol{P}})}{\sqrt{\sum_{n=1}^{n}(\boldsymbol{O}_{i}-\bar{\boldsymbol{O}})^{2}}\sqrt{\{\sum_{n=1}^{n}(\boldsymbol{P}_{i}-\bar{\boldsymbol{P}})^{2}\}}} \qquad \textit{Equation 5}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}(|P_i - O_i|) \qquad \textit{Equation 6}$$

where P is the RCM data, O the reference data at timestep i, and n the number of data points. $\overline{O}$ and $\bar{P}$ are the mean value of the reference and RMC data, respectively *(Ndiaye et al., 2022; Gerasu et al.,2023).*

3. Climate change affecting electricity demand.

Various weather and climatic parameters influence electricity demand and are qualified as energy-related climate variables: temperature, humidity, solar radiation, wind speed, precipitation, etc. Hence, it is essential to estimate the values of cooling degree days CDD and heating degree days HDD to account for energy requirements driven by the change in climate. CDD and HDD have been indicated as effective metrics to quantify cooling and heating demand respectively. *(Ahmed et al., 2012 ; C. Huang et al., 2021 ; Qin et al., 2020 ; Schaeffer et al., 2012*). The sums of positive and negative variations in the actual temperature from the base temperature during specific time periods are known as HDDs and CDDs (Cooling or Heating Degree Days) (◦C d). The base temperature is defined as the temperature level where neither heating nor cooling is required *(Huang et al., 2021).* Therefore, changes in CDD and HDD values in the future can be estimated by shifting temperature values to a higher level compared to average temperature. Considering the geographical location of the country, the heating requirement is considered negligible; hence, to estimate the country's future energy demand for cooling-driven climate change, the cooling degree days (CDD) are considered and estimated as follows:

$$CDD \ = \sum_{i=1}^{n}(T_i - T_b)(T_b \leq Ti) \qquad \textit{Equation 7}$$

where n: the number of days in a year,

T_i is the mean air temperature at day i,

T_b is the threshold of balance point temperature where the electricity demand is a minimum, assumed to be 18 ◦C following *(Qin et al., 2020).*

4. Climate impact on energy generation resource

a. Solar energy potential variation

The PVP depends on the solar resources available at the location, the air temperature, wind speed, cloud cover, aerosols, the spectral distribution of incident radiation, the angle of incidence of radiation, and the operational efficiencies of system components *(Kafka and Miller., 2019).* The PVP describes the performance of the PV cells regarding their nominal power capacity according to the actual ambient conditions, and it is dimensionless *(Jerez et al., 2015)*. PV power generation is defined as the amount of energy received from the sun at the Earth's surface and converted into electricity through PV cells, modules, and arrays *(Sawadogo et al., 2020)*. Climate uncertainties have a direct impact on PV systems' performance and their components. The effect of aerosol concentrations on PVE is evaluated by performing climate simulations under different future emission scenarios *(Gaetani et al., 2014)*. The operating voltage of a PV cell can be affected by the rise in ambient temperature, the level of solar irradiance, cleanliness, and shading effects, thus altering the reliability of the power system. The impact of climate change on PV potential is expressed considering the expression stated *(Sawadogo et al., 2020)*. studies have based their calculations of solar cell temperature on solar irradiance and ambient temperature alone *(Sawadogo et al., 2021)*. Models include the influence of wind speed and relative humidity in calculating the impacts of temperature on PV cells *(Sawadogo et al., 2020),* while others consider the contribution of each variable of the following variables: the solar irradiance (at the plane of the array), the temperature, the wind speed, and the relative humidity to the anticipated potential changes over the study area. Hence, the potential of PV power is expressed as:

$$PVP = P_r(t) * \frac{R_S(t)}{R_{STC}} \qquad \textit{Equation 8}$$

where R_{STC} is the solar irradiance at Standard Test Conditions (STC), which is equal to 1000 W/m2

Pr (t) is referred to as the performance ratio, which accounts for changes in the efficiency of the photovoltaic cells due to changes in temperature *(Jerez et al., 2015)*and is computed as:

$$P_r(t) = 1 + \gamma * (T_{cell} - T_{STC}) \qquad \textit{Equation 9}$$

Where TSTC is the ambient air temperature at STC and is equal to 25 °C. The constant γ depends on the type of solar cell, and we use in this study a monocrystalline silicon solar cell (the most used in Africa) for which γ takes the value of – 0.005 °C−1 (Jerez et al. 2015).

In the cases, where only solar irradiance, air temperature, wind speed and relative humidity is considered, Tcell (°C) the solar cell temperature is expressed as equation in *(TamizhMani et al., 2003; Sawadogo et al., 2020).*

$$T_{cell} = c_1.R_S + C_2.T_s + c_3.W_s + c_4.R_h \text{ ....} \quad \textit{Equation10}$$

with c = 1.57°C; c1 = 0.0289°C/W/m2; c2 = 0.961; c3 = -1.457°C/m/s; and c4= 0.109°C/Rh% where c, c1, c2, c3 and c4 are system-specific regression coefficients determined by *TamizhMani et al., (2003).*

Recent studies have also shown that the contribution of wind speed and relative humidity to changes in PVP is negligible in Africa *(Sawadogo et al., 2019b; Bichet et al., 2019).* Therefore, Tcell is expressed as a function of solar irradiance (Rs) and air temperature (TAS).

$$T_{cell} = C_1 + C_2 * TASMAX + C_3 * R_S \text{.....} \qquad \textit{Equation 11}$$

The coefficients c1 = 3.75 °C, c2 = 1.14, and c3=0.0175 °C m^2 W−1 for a monocrystalline silicon cell were taken from *(Lasnier and Ang., 1990)* and used in *(Crook et al., 2011).*

b. Wind power density:

The potential for producing wind energy is gauged by the wind power density (WPD) of a site. The wind power density (WPD) of a turbine depends on air density and wind velocity. The wind power density (WPD) of a turbine is affected by air density and wind velocity (speed). *(Costoya et al., 2019).* Here, WPD (W/m2) is expressed as follows: It is calculated according to the following expression *(Sawadogo et al., 2019).*

$$WPD = \frac{1}{2} * \rho * V^3 \qquad \textit{Equation 12}$$

where ρ is air density (kg/m3) and V is wind speed (m/s) at the desired height. Since ρ is a function of elevation (Z), we estimate it following *Custódio., (2009)*:

$$\rho \cong \frac{353.4(1-\frac{Z}{45271})^{5.2624}}{273.15+T} \qquad \textit{Equation 13}$$

where Z is considered the elevation (in metres), and T is the air temperature at 100 m. The parameter T is calculated by considering a dry adiabatic lapse rate of about 1 °C per 100 m *(Wallace and Hobbs., 2006*). The same method was used by *Reboita et al., (2017)* to estimate ρ in the calculation of WPD over Southern America.

IV.6. Conclusion:

This chapter has discussed the research methodology used in the study. It explains data collection methods, data sources, how they were accessed, the data analysis process, and the rationale behind choosing the methods, models and tools. Overall, it provides a comprehensive overview of the methodological framework towards achieving a sustainable energy supply for all and long-term energy systems sustainability; by taking into consideration the international policies on climate change and the Malian commitment (NDCs).

Chapter V: Results and Discussions

V.1. Evaluation of the country's current energy situation

1. Current state

The current energy situation of Malian energy is depicted in figures 18, after careful consideration of the different sectors, the general observations are the following: the final energy consumption had almost doubled from 2010 to 2019 and has been increasing since the net import which includes the import of electricity, oil products and natural gas have also been highly increasing. On the other hand, the country electricity production has seen a slight increase during the last years before the political crisis, unfortunately been insufficient to cover the total energy demand. The final demand is largely superior to both the production and the power imported which is a major reason for the supply system's unsustainability.

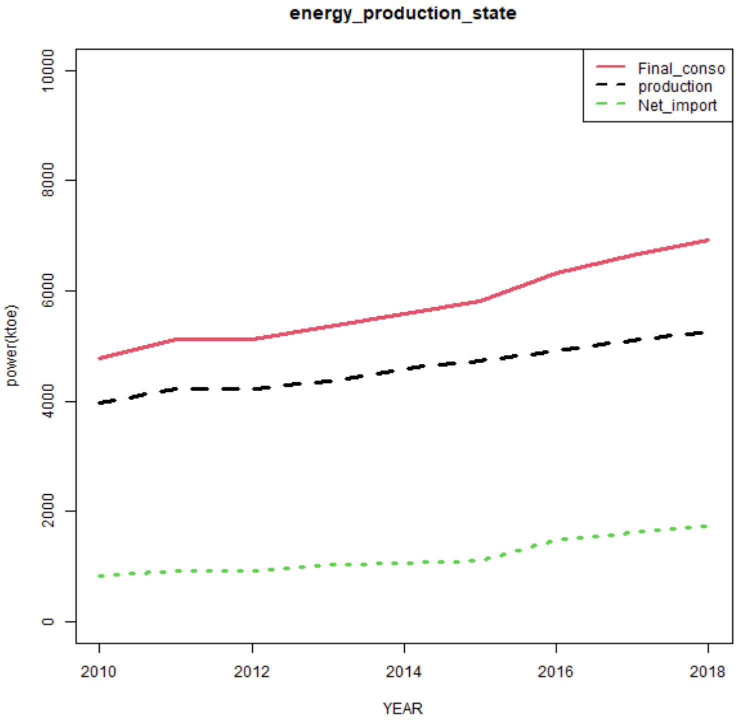


Figure 18: final energy consumption pattern

Domestic energy or cooking energy consumption had been set to significantly increase as to the prediction for the year 2030 (figure 19) in the various policy and energy supply strategies. The demand for charcoal was set to grow twice than that of firewood. The strategies also spoke of an increase in the import of natural gas which would help decrease the reliance on charcoal and firewood consumption in the future. Furthermore, it also spoke of the introduction of biogas and bioethanol produced from waste and agricultural residues. Unfortunately, the country has assisted in the shortage of natural resources leading to the price increase in cooking wood fuel and charcoal.

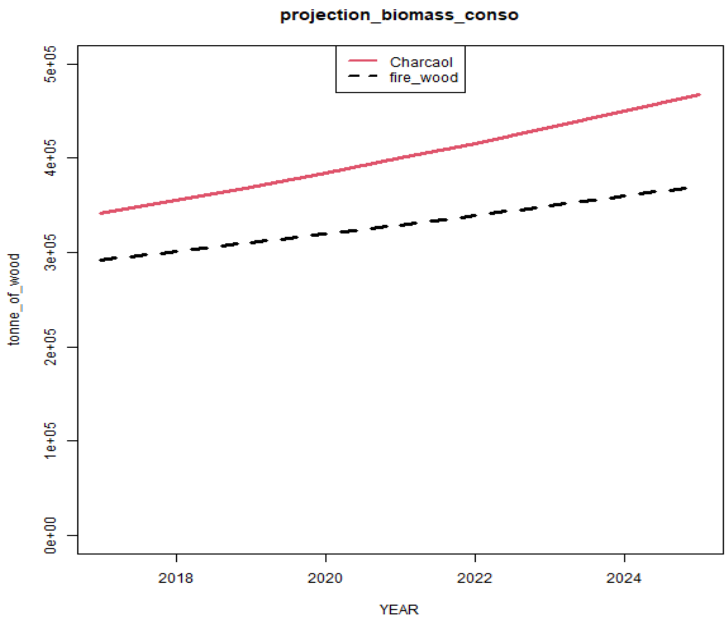


Figure 19: domestic energy consumption evolution

2. Strategies and planning

The planned expansion (figure 20) in electricity production capacity predicted an increase in hydropower production, development of between country electricity sharing through the interconnections (energy sharing from neighbouring countries) and the deployment of different renewable energy resources (mostly solar and wind). Importantly the strategies predicted an increase in the net energy import, the sustainability of which in the face of the political crisis of today (2022) is yet to be redefined. Thermal energy production was predicted to decline from 2017 from the current situation, thermal production is the main power production of the country therefore exposing the country energy sustainability to oil price increase, petroleum products import condition (non-availability of the resources in the country). Hence there is an urgent need to restructure the country's energy system by updating the various policy documents and strategies linked the energy production and supply.

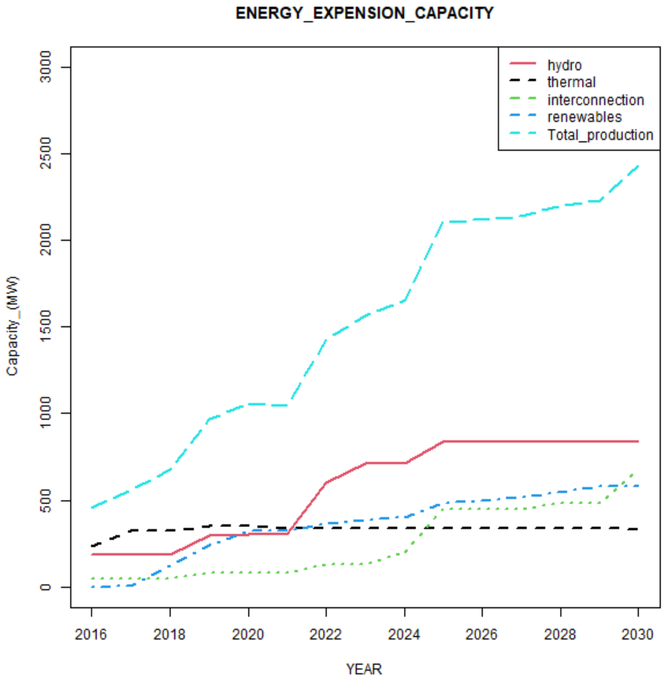


Figure 20: power system expansion plans

3. Situation analysis

The Malian current energy situation Mali has seen a deep setback especially these last years. The power supply is at its lowest point of sustainability yet 12 to 24h daily load shedding. The current situation is due to various factors: high demand growth, oil product price increase, the reliance on fossil fuel products, the non-integration and non-development of renewable energy resources into the mix and more importantly the political situation making sustainability needs of this system more pressing. The situation is in total contradiction to the one planned in the different energy supply strategies and the policy document (PANEE, PANER). The strategies and plans that have so far governed the Malian energy supply systems need a more thorough revision and update.

V.2. Sustainability assessment of the country energy system

Analysis of energy supply scenarios and projection to 2050. Table 12 presents the detail energy scenario composed of share of different technology in the different scenarios. Business as usual BAU consists mainly of traditional biomass, petroleum products, thermal energy, and hydropower, in the other alternative scenarios (S1, S2, S3, S4 and S5) include renewable energy components and natural gas which have a huge potential in the country. The energy demand of Mali grows annually at a rate of 10% *(AfDB., 2015)*, which is maintained constant to assess the future evolution of the energy supply systems during the period of analysis. The evolution of each share from 2018 to 2050 is presented in Figure 21.

Table 12: Detailed share of energy sources for different alternatives of energy supply in Mali

Energy technology share (%)	S0 (BAU)	S1	S2	S3	S4	S5
Biomass (Traditional)	74	50	40	27	10	10
Biomass (Modern)	-	10	20	10	5	5
Petroleum Product	22	23	20	20	10	10
Natural Gas	-	-	3	3	5	5
Electricity supply	4	17	17	40	70	70
Hydro*	(50.7)	(20)	(30)	(25)	(25)	(18.4)
Thermal*	(46.9)	(30)	(15)	(15)	(0)	(38.1)
Bioenergy	-	(3)	(15)	(15)	(25)	(0)
Solar*	(2.4)	(28)	(30)	(30)	(35)	(22)
Wind*	(0)	(2)	(10)	(10)	(10)	(0)
Import*	(17)	(17)	(0)	(5)	(5)	(41.3)

*: Share (%) in electricity production

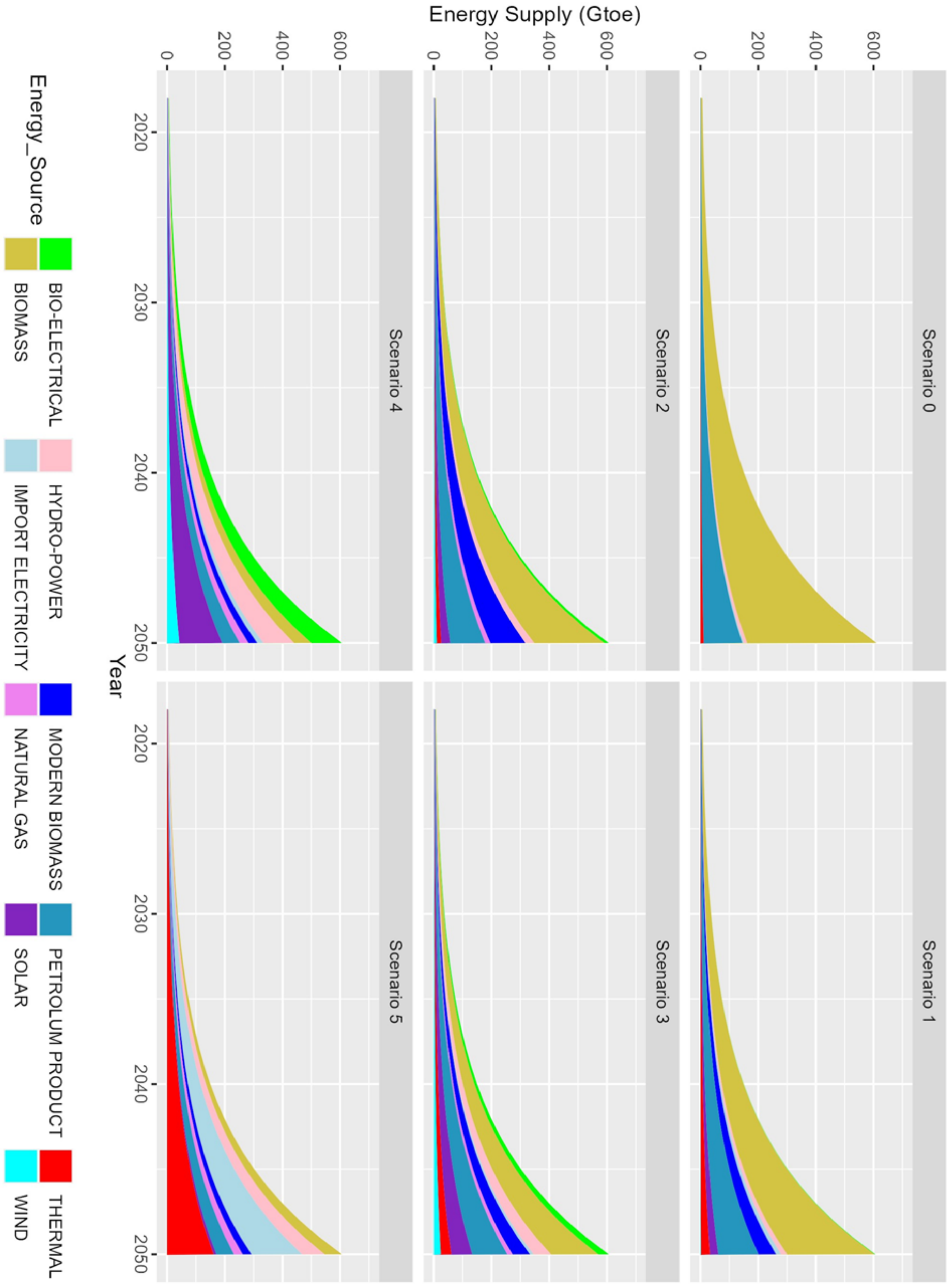
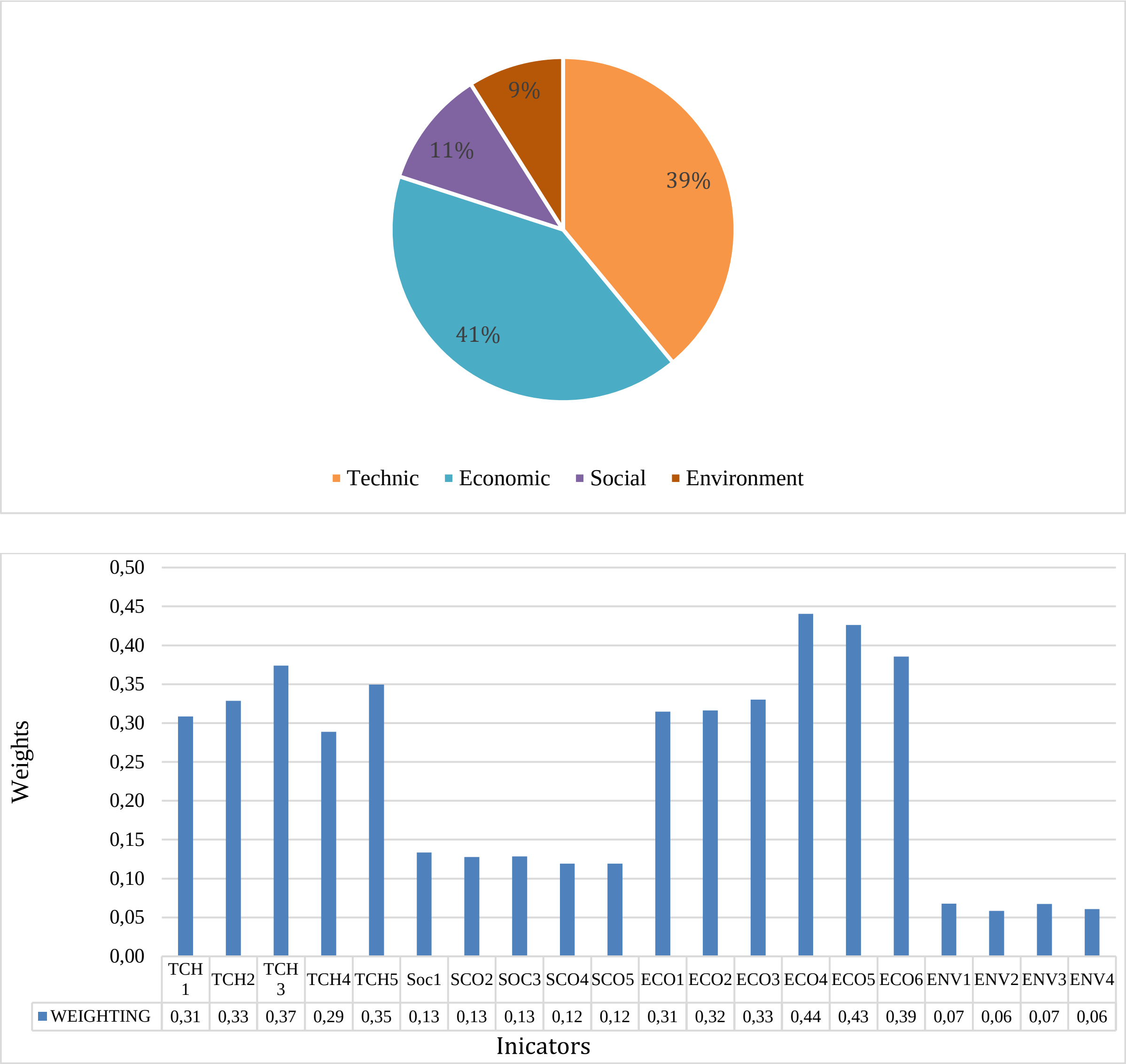


Figure 21: Evolution of the energy supply systems to 2050 when considering the assumptions of the six scenarios

Figure 21 gives a graphic representation of each energy supply scenario. It appears that the scenario BAU is the less diversified energy supply option based on the use of traditional biomass (charcoal and firewood) which will increase to 500 Gtoe in 2050 (scenario 0). The forests of Mali will not be able to support such a production of firewood and charcoal which, moreover, already suffer from the combined effects of overexploitation and desertification *(CPDN., 2016).* Scenarios 2, 3, 4 and 5 all consist of well diversified sources of energy supply. The share of traditional biomass is still significant in scenario 1 and 2 while scenario 5 supports the excessive use of thermal plants and the import of electricity both projected to 150 Gtoe in 2050. Energy supply sources are better balanced in scenario 3, unlike scenario 4 which calls for intensive use of renewable sources up to around 150 Gtoe in 2050.

1. Weighting Coefficient for Dimensions and Indicators

The weighting coefficients of the four dimensions as well as for each of the 21 sustainability indicators were analysed with respect to the current energy situation of the country and the priority defined by stakeholders' survey. The six defined scenarios are examined under each of the four dimensions. The weighting coefficients in Figure 21 reveal the prioritisation of energy stakeholders, which has shown a preference for the economic and technical dimensions with respectively 41% and 39 % of the average weights for sustainable energy planning in Mali. Then, the social and environmental dimensions have been given the least important weight with 11% and 9% respectively. The normalized mean values are used as the basis to estimate the weight coefficient of indicators (Figure 22). It also gives an idea of the importance of each indicator considering a common scale, thus allowing the comparison of the alternatives. The three highest priority indicators by stakeholders are all under economical dimension (ECO4: Investment cost ECO5: Payback period and ECO6: Government support). Then, the indicator TCH3: the resources potential under the technical dimension. The energy stakeholders' choices of priorities are in favour of the economic and technical indicators for the energy sustainable supply assessment, which undermined the environmental indicators which are important aspects of the sustainability of the energy supply system considering they reflect the impacts of an energy supply system on environmental sustainability hence mitigating climate change *(Liu., 2014).*

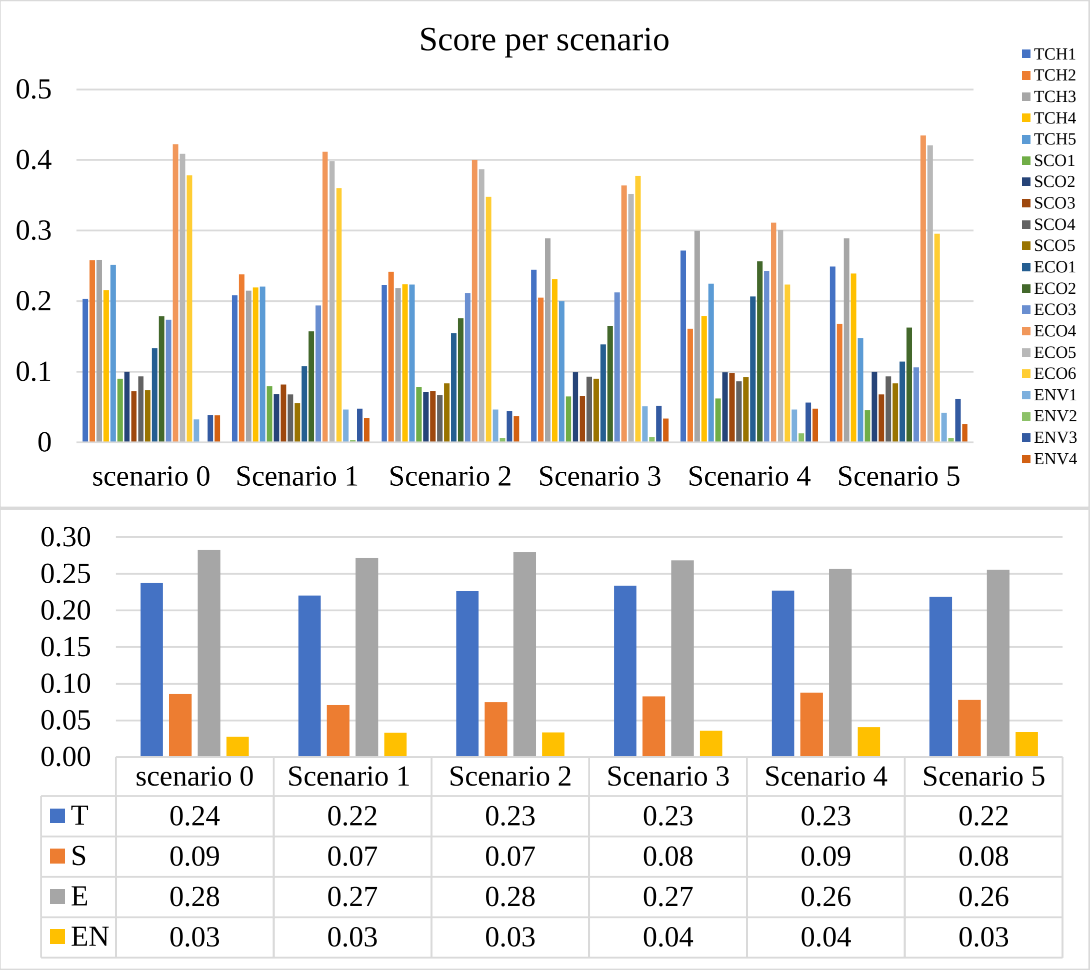


	TCH 1	TCH2	TCH 3	TCH4	TCH5	Soc1	SCO2	SOC3	SCO4	SCO5	ECO1	ECO2	ECO3	ECO4	ECO5	ECO6	ENV1	ENV2	ENV3	ENV4
■ WEIGHTING	0,31	0,33	0,37	0,29	0,35	0,13	0,13	0,13	0,12	0,12	0,31	0,32	0,33	0,44	0,43	0,39	0,07	0,06	0,07	0,06

Figure 22: Normalised value of criteria weight

2. Ranking of scenario under each dimension

(Figure 23) depicts the ranking of the various criteria of each scenario for the MCDM evaluation. The criteria don’t have the same importance; the scenarios also will have criteria with different importance. The ranking of all criteria for each scenario are highlighted (Figure 22). The indicator with the highest ranking is ECO4 followed by ECO5 in all scenarios, except scenario 3 where ECO6 is the most performing. For Scenario BAU, criteria ECO4, ECO5 et ECO6 are the most performing and the environmental indicators own the smallest ranking. Scenarios 1, 2, 3, and 5 exhibit a similar pattern as BAU with a high preference for economic indicators while the environmental indicators are least performing. For scenario 4, the economic indicators are balanced by the technical factors and the small scores are observed for environmental indicators.



	scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
T	0.24	0.22	0.23	0.23	0.23	0.22
S	0.09	0.07	0.07	0.08	0.09	0.08
E	0.28	0.27	0.28	0.27	0.26	0.26
EN	0.03	0.03	0.03	0.04	0.04	0.03

Figure 23: Ranking of indicators for each scenario

a. Technical Dimension

The evaluation of the six proposed energy supply alternatives including the Business as usual according to the technical dimension is here presented. The dimensions TCH1: production efficiency, TCH2: capacity factor, TCH 3: RP (resources potential, toe), TCH4: reliability of the system, TCH5: resources availability (toe) having different weights are used for the assessment. It resulted that the scenario BAU showed the best performance and obtained by far the highest overall score followed by scenario 3. This finding is in confirmation of several studies demonstrating that scenario-driven fossil fuels together with hydropower scores better results under technical dimension attributed to those technologies' stability, reliability, and maturity *(Afgan and Carvalho., 2004; Bhandari et al., 2021)*. Scenarios 1,5,2 and 4 obtained the lowest score in that dimension. This could be explained by the high share of renewable energy in Scenario 4 and the important energy import contribution in Scenario 5 evidence of generation stability and high dependency on weather conditions of those energy resources.

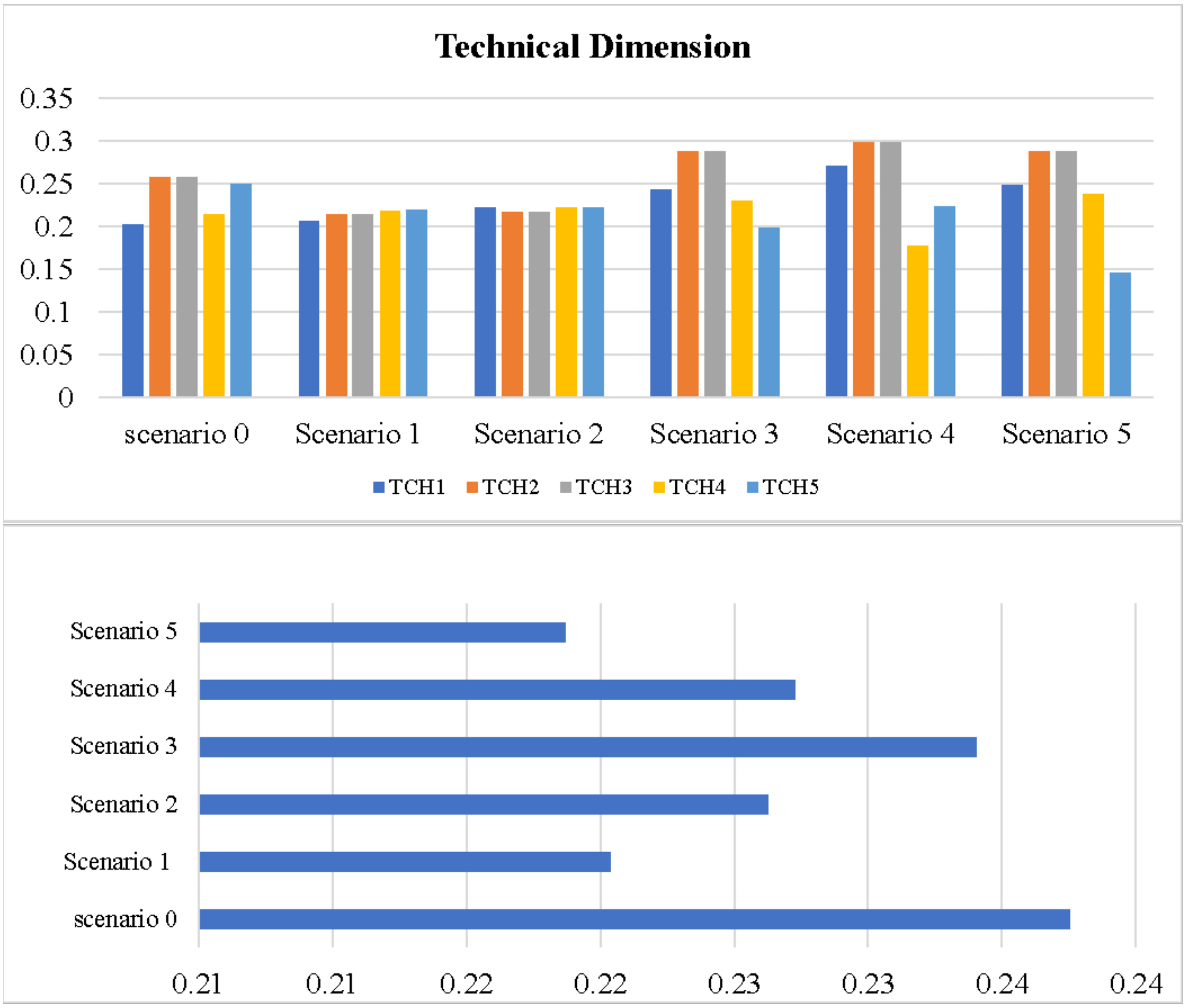


Figure 24: Score per scenario for technical dimension

b. Social Dimension

In the present study, the social dimension was given 11% of weight importance (Figure 22). Under this Dimension, different selected alternatives are evaluated with respect to indicators SCO1: Energy Acceptance, SCO2: Energy Accessibility, SCO3: Job creation (Job. /Mw), SCO4: Energy Affordability, and SCO5: People Displacement. Considering the scenario performance by criterion, Energy Accessibility presents the highest ranking for all scenarios. Scenario 4 scores the best performance and exhibits a high rank for indicator SCO3 which Favours job creation. Scenarios 3 and 5 come closer to BAU considering the criterion SCO4, energy affordability. Indeed, BAU is the most affordable (Figure 25) since it is based on the use of biomass (74% share in the mix) from the country's forest reserves, which is due to the low cost of purchasing. Charcoal and wood fuel (in this scenario) are the most socially accepted and affordable technologies in Mali like in other developing countries *(Bhandari et al., 2021)*. The overall performance of Scenario 4 compared to others can be explained by the fact that renewable energy responds better to social criteria than fossil energy, and it has the worst performance when it comes to the evaluation criteria SCO5 favouring limiting people displacement. Thus, Scenario S4 becomes the one to be considered for socially sustainable energy planning for sustainable energy supply in Mali.

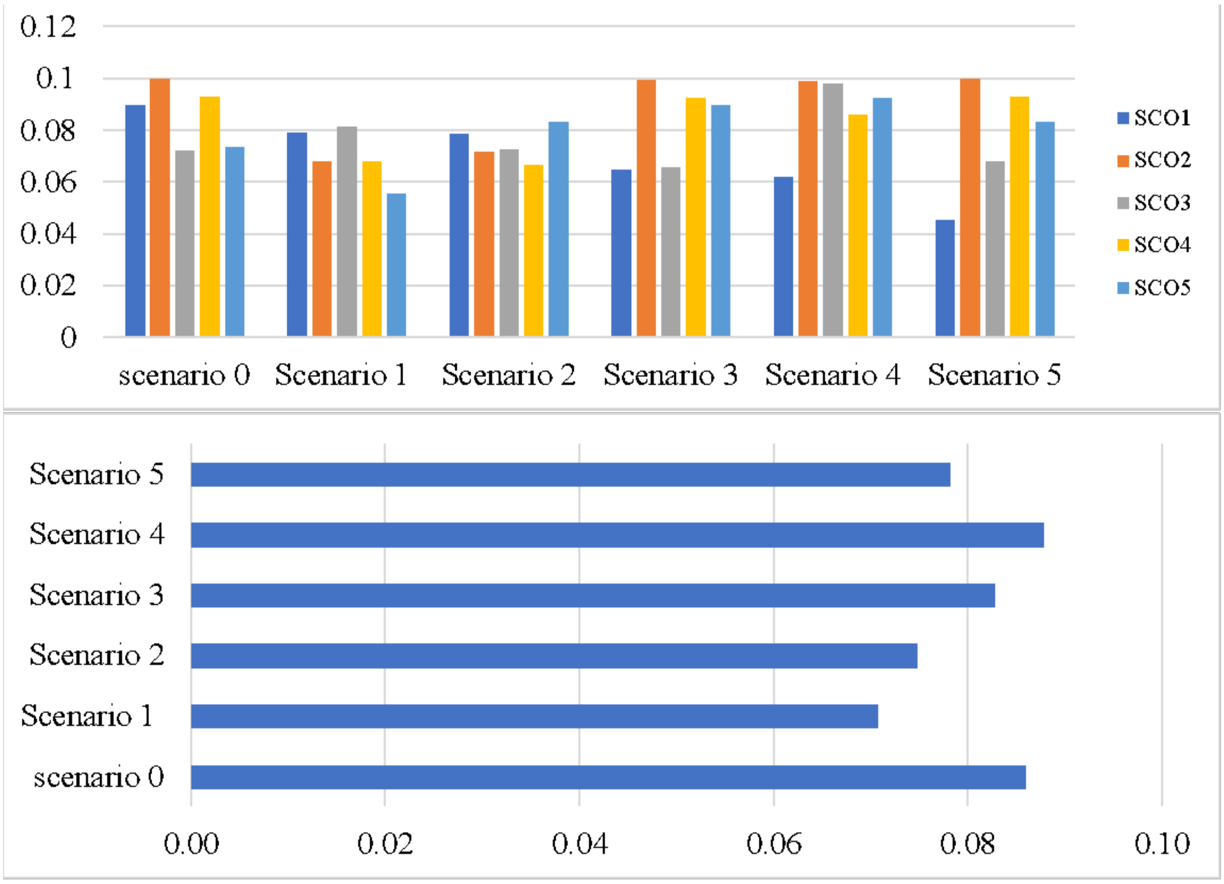


Figure 25: Score per scenario for social dimension

c. Economic Dimension

Assessing of economic impact of energy supply options, the following indicators have been used ECO1: energy dependency (%), ECO2: net import dependency (%), ECO3: fuel cost ($/GJ), ECO4: LVC USD/ KWH, ECO5: investment cost (€/KW), ECO6: payback period (year), ECO7: government grant/support, which has critical weight consideration for the assessment. The result shows that scenario BAU was the most sustainable economically. The economic affordability of the BAU scenario could be explained by the low fuel cost, low investment cost, and most importantly the low energy dependency on this scenario's resources. Alternatively, to BAU, scenario 2 is the most performing for sustainable energy supply. With 34% of renewable energy, scenario 2 is based on the economic advantage of offering renewable energies. Which have become more cost-effective than most fossil fuel technologies in recent years *(Shaaban et al., 2018).*

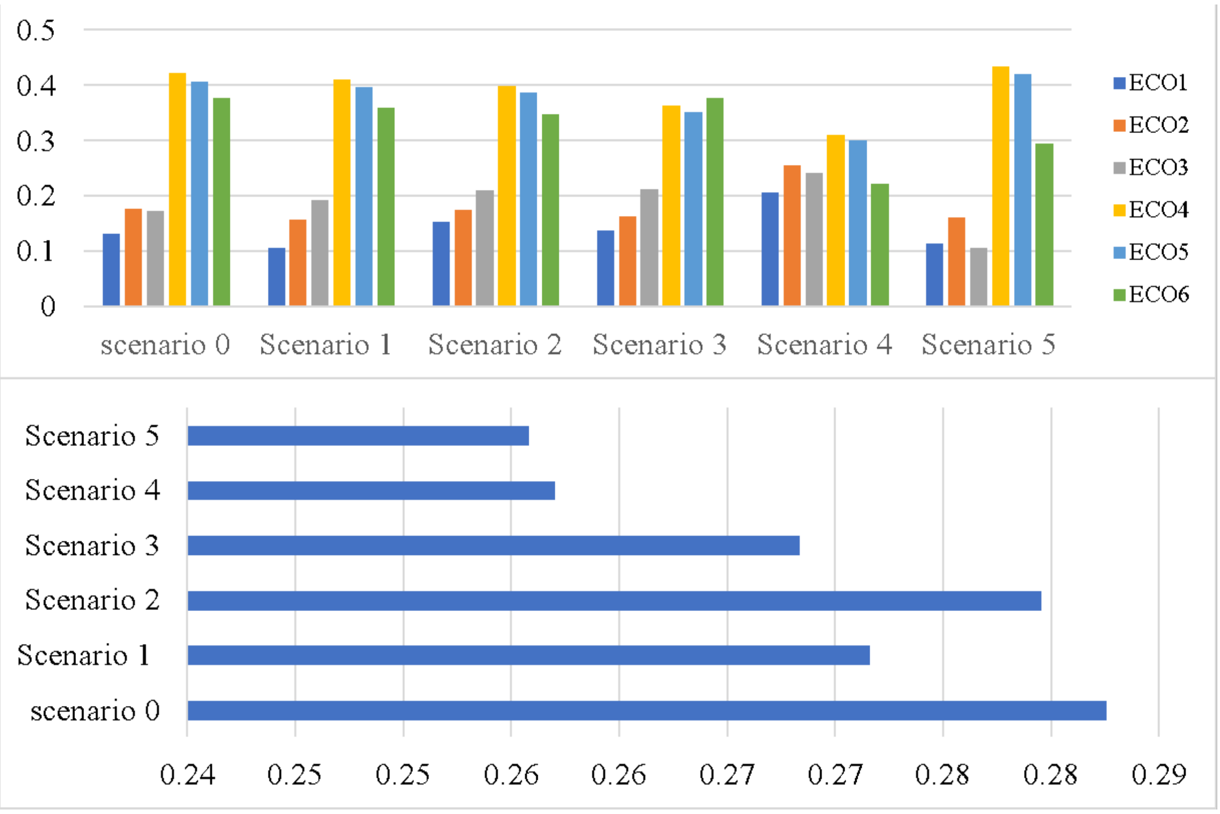


Figure 26: Score per scenario for Economic dimension

d. Environmental Dimension

The selection of potential sustainable energy mix supply options for this study gives particular attention to the environment considering indicators (Figure 27); ENV1: Energy Diversification, ENV2 Fraction of Renewable Energy, ENV3: Land Use and Rate of Deforestation (M2/Mwh), ENV4: Emission (Gco2e/Kwh) criteria for the assessment. In all scenarios, the indicator ENV3 ranks the greatest scores (Figure 26) with its highest value being in scenario 5 which favours energy import. Thus, land deforestation is a priority indicator for all supply energy options. Scenario 4 presents the best energy supply options by considering the environmental dimension with more priority given to indicators related to land use and deforestation (ENV3) and the potential for global warming due to CO2 emissions (ENV4). Indeed, the carbon intensity of energy production and supply is the principal driver of energy-related environmental issues. So, besides the advantage of reducing the emission and global warming potential of the systems, renewable energy systems can cause high land demand (their low intensity) and cause deforestation in the country *(Afgan and Carvalho., 2004; Akan et al., 2015)*, particularly the photovoltaic technology which represents the heightened renewable energy potential in Mali. Impacts could be variability of rainfalls and deforestation which could be particularly harmful to the Malian energy systems based on biomass and hydropower. The high score of the energy diversification indicator (ENV1) for all energy supply alternatives to BAU attests to the importance of environmental benefits as it prevents relying on fossil fuels that are harmful to the environment.

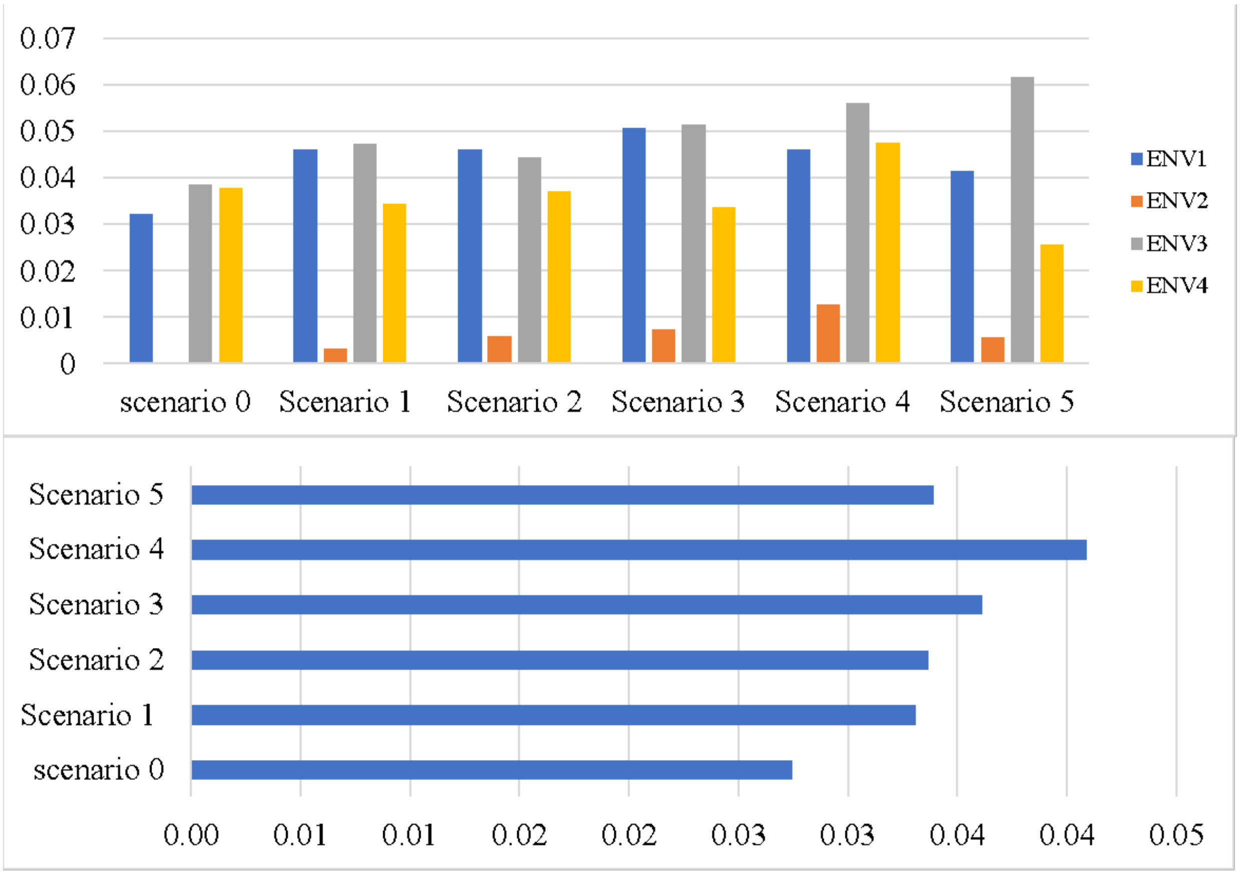
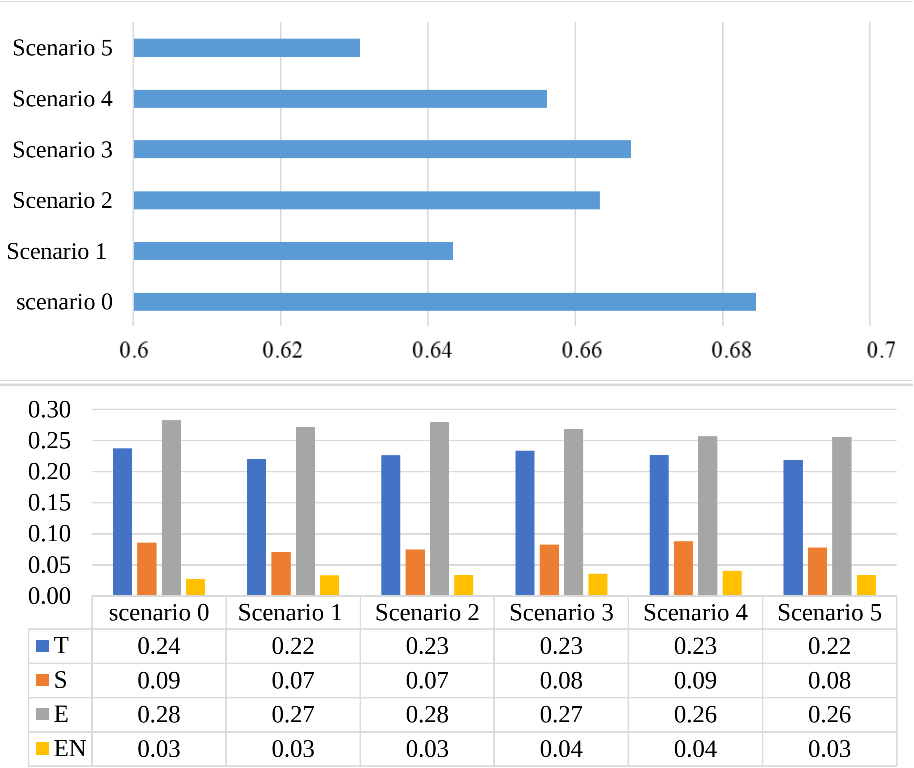


Figure 27: Score per scenario for Environmental dimension

e. Overall Scores of scenarios

The BAU and the five alternatives' scenarios are given an overall score, and the highest value is then presented as the sustainable option for Malian's energy path. After aggregating the indicator, it was discovered that scenario BAU performs the best, with a normalised score of 0.68, followed by scenarios 3, 2, 4, 0, 0, 1, and 5, with scores of 0.66, 0.66, 0.65, 0.64, and 0.63, respectively (Figure 28). Although BAU initially performed well based on the aggregated score of the evaluation, the energy imports of 17% have not been considered for this scenario, which is why it has emerged as the best Scenario. Therefore, Scenario 3 (Petroleum product: 29%, Renewable energy: 42%, Biomass: 27%, and Energy Import: 2%), which is based on a shift in the country's energy system toward the development of renewable energy, is the most sustainable energy supply scenario to consider for the Malian energy planning.

In comparison to hydropower and electricity produced from fossil fuels, renewable energy is a clean technology with great potential for the country, high levels of public acceptance, and low greenhouse gas emissions. The deployment of renewable technology has several drawbacks, including high investment costs, production dependence on weather, and relatively low efficient conversion *(Bhandari et al., 2021)*. Such problems can be overcome by the adoption of certain measures such as a strong political will that leads the authorities to invest in subsidising all the equipment of renewable energy technologies to make the cost more affordable and policies that encourage the population to use renewable energy (such as lower taxes and duties). In addition, problems related to intermittency and production inefficiency can be mitigated by interacting with the energy storage options.



	scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
🟦 T	0.24	0.22	0.23	0.23	0.23	0.22
🟧 S	0.09	0.07	0.07	0.08	0.09	0.08
⬜ E	0.28	0.27	0.28	0.27	0.26	0.26
🟨 EN	0.03	0.03	0.03	0.04	0.04	0.03

Figure 28: final score of scenarios (upper panel) and per dimension (bottom panel)

Nevertheless, findings regarding the sustainability of renewable sources of energy supply are in line with previous investigations revealing the huge potential of renewable energy, especially solar PV as a better option for power supply in Mali *(Diarra and Akuffo., 2001; Sessa et al., 2021*). Results further converge toward the ensemble of energy supply policies and strategies in Mali as well as international pledges (sustainable development goals and Paris Agreement) all promote the introduction of clean, affordable renewable energy in the country system to limit the CO2 level in the atmosphere. In addition, sustainable long-term energy planning should focus on the development of renewable energy *(Zelt et al., 2019)*. Hence, the transition towards renewable energy technologies (Scenario 3) is the most sustainable, since there is evidence that renewable energy adoption and development is driving economic growth and decreasing environmental impact through the reduction of emission of greenhouse gases *(Qudrat-Ullah and Nevo., 2021)*. These results also support the country's NDC which targets to reduce the GHG emissions from energy sources by 31% in 2030 *(NDC., 2021).*

V.3. Evaluation of climate change impacts on energy systems

1. Evaluation of the climate model simulation

a. Capability of selected GCM

The statistical tools and measures considered here to quantify the accuracy of the GCMs are the followings: square error (RMSE), mean absolute error (MAE), and (Pbias) were used to determine model performance.

Table 13: statistics of the various GCMs

Statistic /Model	**MIROC-MIROC5**	**NCC-NorESM1-M**	**CCCma-CanESM2**	**HADGCEM**
Cloud cover				
Pbias (percentage bias)	1.3	4.3	2.5	1.3
Mean absolute error	8.77552	13.7752	8.09504	7.250103
RMSE,	11.4281	16.2996	10.4487	9.8855
tasmax				
Pbias (percentage bias)	-0.1	-0.1	0	-0.3
mae	1.2388	1.4641	1.59957	1.36331
RMSE,	1.5689	1.775	1.9434	1.7223
rsds				
Pbias (percentage bias)	1.3	4.3	2.5	1.3
RMSE	11.42811	16.2979	10.8428	9.885

mae	8.7755	13.0013	8.0095	7.25010
Sunshine duration				
Pbias (percentage bias)	0.3	1.2	1.1	0.3
mae	416.146406	556.1742	441.451	326.29117
RMSE,	552.2908	742.2909	606.74921	463.9348

b. Evaluation at Seasonal Scale:

Figure 29 and Figure 30 present the intern-annual mean and monthly cycle, respectively, for the reference period of 1981–2005. The variables clt (total cloud fraction), sfcWind (near-surface wind speed), rsds (surface downwelling shortwave radiation), hurs (near-surface relative humidity), tasmax (daily maximum near-surface air temperature), and pr (precipitation) were evaluated.

c. Annual cycles of monthly climatology

For each of these variables, the performance of the four selected models to represent the annual cycle was assessed in comparison to observational data. The evaluation revealed that the models generally succeeded in capturing the overall patterns and amplitudes of these variables. The simulations generally show similar patterns to the observation. However, most models tend to slightly underestimate/ overestimate the observation. It is important to note certain discrepancies identified, particularly in relation to cloud cover, where both overestimations and underestimations were observed. It appears that the models exhibited a relatively lower level of performance in replicating the precise pattern of cloud cover. Despite these discrepancies, the models demonstrated effectiveness in replicating the amplitudes of the variables, signifying their capability to simulate annual patterns effectively. It is also worth mentioning that the simulations tended to overestimate sunshine duration and short-wave radiation while underestimating precipitation and humidity in the context of near-surface temperature. The models appear to display fewer biases compared to the observations. The same remarques for the sunshine duration the models presented well the pattern of the variable however all slightly overestimated. Reciprocally for the short downward radiation where the variable trend was also overestimated the four analysed GCM simulations slightly overestimated short-wave radiation. The results suggest that the models performed well at representing sunshine duration, short wave radiation, and temperature.

Conversely, the four models show less performance in representing precipitation and humidity and cloud over very particularly the most biased was identified (table 13)

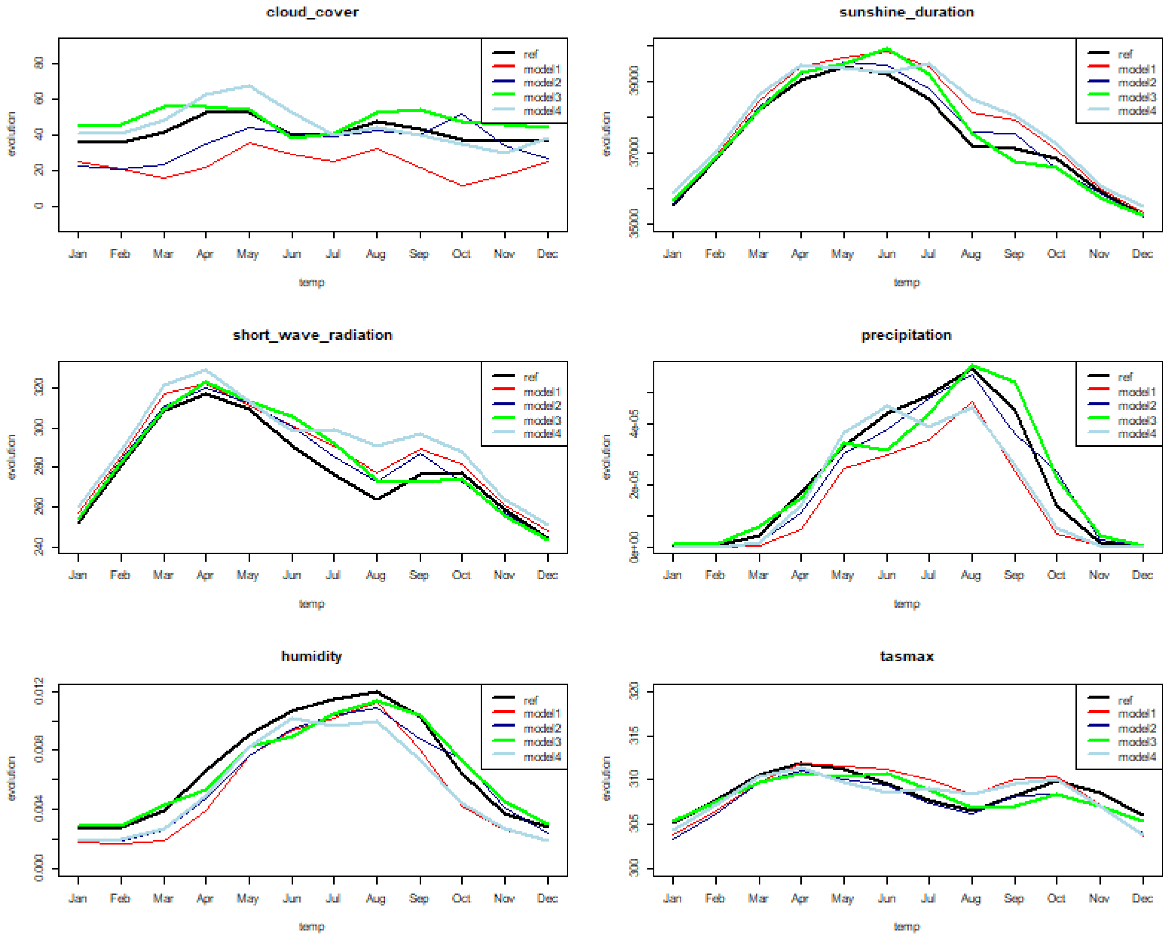


Figure 29: Mean monthly (monthly variability) cycle: precipitation, surface air temperature, sunshine duration, humidity, cloud cover and shortwave radiation

d. Mean Monthly cycles

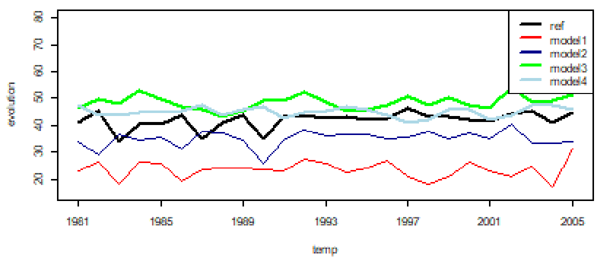
The long-term monthly climatology averaged over the study area was examined, with results presented in Figure 30 for the variables clt (total cloud fraction), sfcWind (near-surface wind speed), rsds (surface downwelling shortwave radiation), hurs (near-surface relative humidity), tasmax (daily maximum near-surface air temperature), and pr (precipitation).

The inter-annual variability assesses the capability of the models to depict the measured deviation from the climatological average for variables for the period of study (1981–2005). The deviation reveals the magnitude of how big or small a specific year’s total precipitation or average temperature, cloud cover, wind speed, humidity and sunshine duration deviate from the average of the year's total. The inter-annual variability provides information on the consistency of the models compared to the observations.

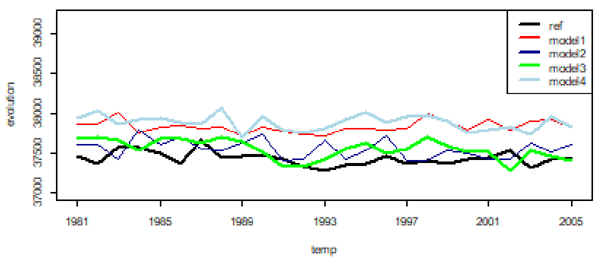
The deviations of the annual mean of the variables from the long-term mean for the period 1981–2005 were examined for all four models for all the variables, and the capability of the model to depict the measured deviation from the climatological average for the period of study (1981–2005) was analysed.

The model's performances were evaluated by calculating whether the annual mean of the variables for a particular year was greater or lesser than the long-term mean for the period 1981–2005. The inter-annual variability provides information on the consistency of the models compared to the observed ERA-INT. The results show that models primarily captured the inter-annual variability that characterised the variables within the study areas, however, with some disparities in magnitude and timing.

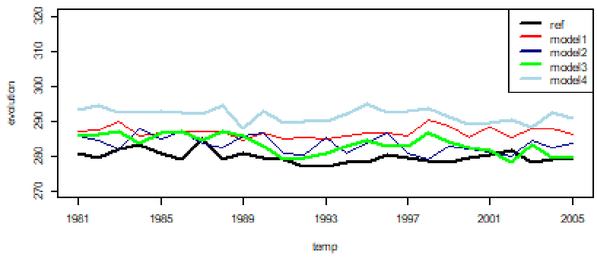
The ensemble of the GCM outputs is relatively good at recreating both the scale and the variability of Maximum Near-Surface Air Temperature (Tasmax), predominantly varying within less than 0.5 °C of the observed data. Most of the model outputs were quite closely grouped together; however, like the precipitation simulations, one GCM-driven RCM simulation was an outlier for the temperature datasets. They were able to replicate the rate of change. The analysis of the mean annual temperature changes in 30-year time slices compared to the 1976–2005 reference period gives an insight into the projected changes during the whole century, dividing it into same-length periods. All the GCM simulations slightly overestimated short downward radiation overall. Levels of precipitation across the country between 1961 and 2005 haven’t varied much; there was a slight increase between 1981–1985, 1985–1990, and 2001–2005, except for Model 3 (expel: NorESM1-M), which overestimated the precipitation. It is to be noted that all the models replicate the annual trend in precipitation over the simulation period, with more or less bias.



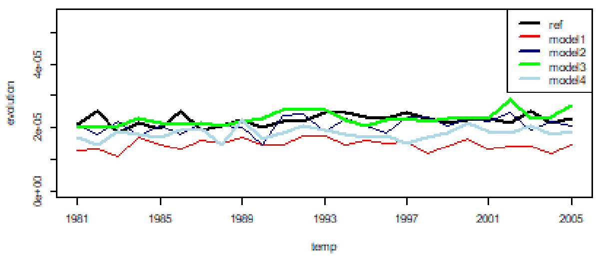
cloud_cover



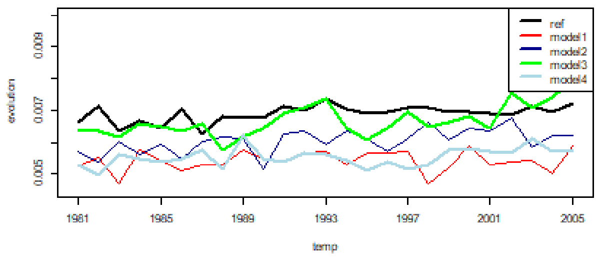
sunshine_duration



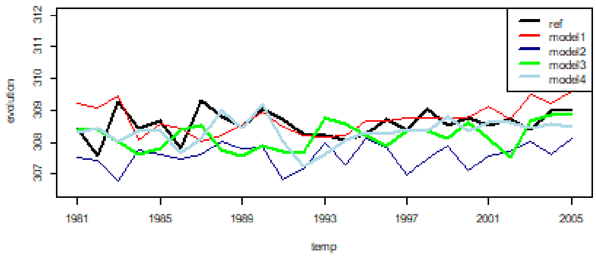
short_wave_radiation



precipitation



humidity



tasmax

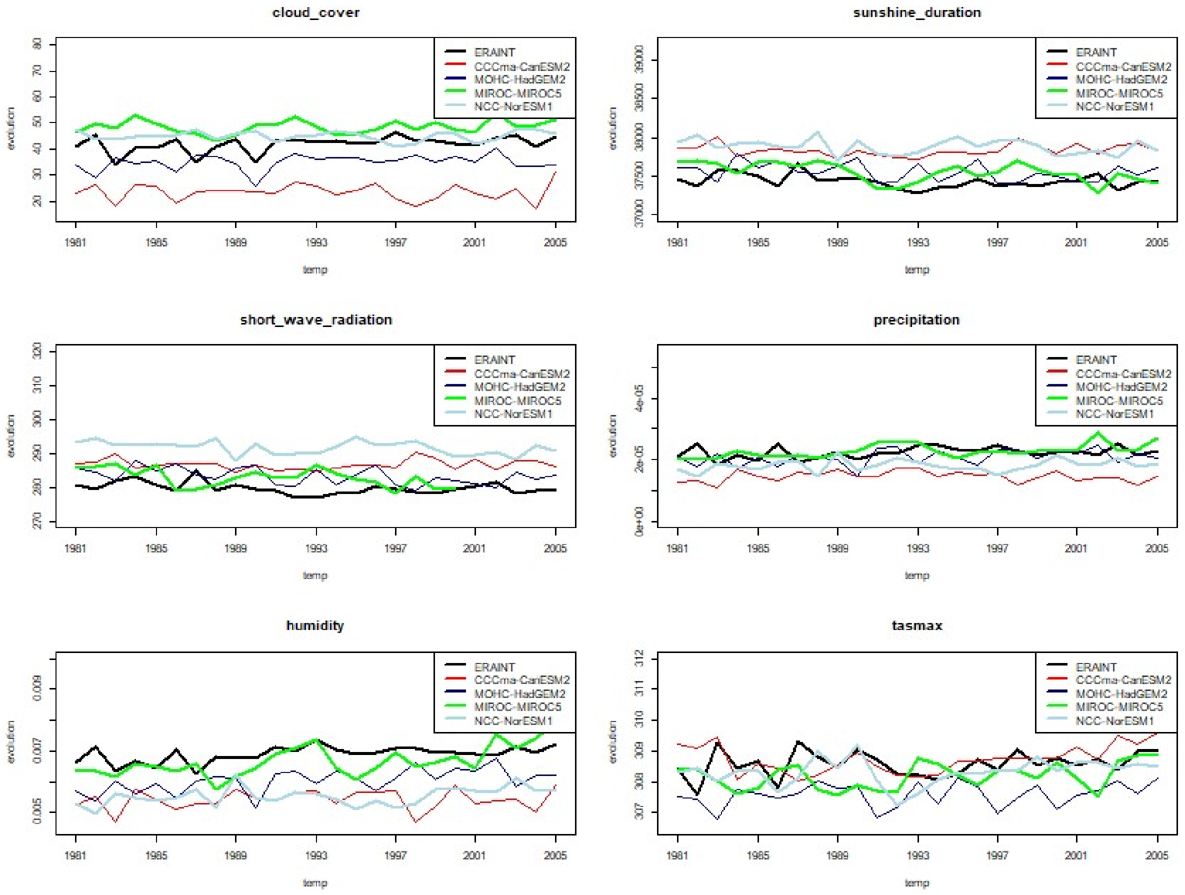


Figure 30: inter-annual variability for: precipitation, surface air temperature, sunshine duration, humidity, cloud cover and shortwave radiation

e. Spatial based Evaluation

To assess the accuracy of the various models' ability to reproduce the spatiotemporal patterns and variability inherent in the models for the various variables, the Taylor diagram (figure 31) represents a statistical summary of simulations and the predictive power of the models in comparison with ERA-INT (the observation), namely deviation (σ), correlation coefficient (r), and root mean square difference. The models showed a positive correlation with the observation (ERA-INT). The performance of the four different simulations vis-à-vis the observations varies depending on the variables considered. Individual variables taken into account, the four simulations perform differently in comparison to the reference data, with the correlation being between (0.90-0.98%) for hurs (Near-Surface Relative Humidity), (0.1-04%) for clt (Total Cloud Fraction), sfcWind (Near-Surface Wind Speed), (0.9-0.95%) for rsds (Surface Downwelling Shortwave Radiation), (0.75-0.85%) for Tasmax (Daily Maximum Near-Surface Air Temperature), and (0.9-0.95%) for precipitation. However, the CCCma-

CanESM2 reproduces the observed spatial pattern well (correlation of 0.91). The best-performing model with the variables: Total cloud cover (clt)/NCC-NorESM1-M, precipitation (pr) MIROC-MIROC5, Shortwave radiation (rsds), MIROC-MIROC5, Sunshine duration (sund), MOHC-HadGEM2-ES Specific humidity (hus850), MIROC-MIROC5, Temperature (tasmax). CCCma-CanESM2. The model CCCma-CanESM2 performed best for most of the variables (humidity, precipitation, sunshine duration, and shortwave radiation), confirming that model CCMA is the best model at representing the climate change projection in Mali. The model MIROC-MIROC5 could give a relatively more accurate projection that would represent the future energy situation of the country. Compared to the other models. Hence, the study highlights the use of future climate impact studies, particularly those concerning the Malian energy sector.

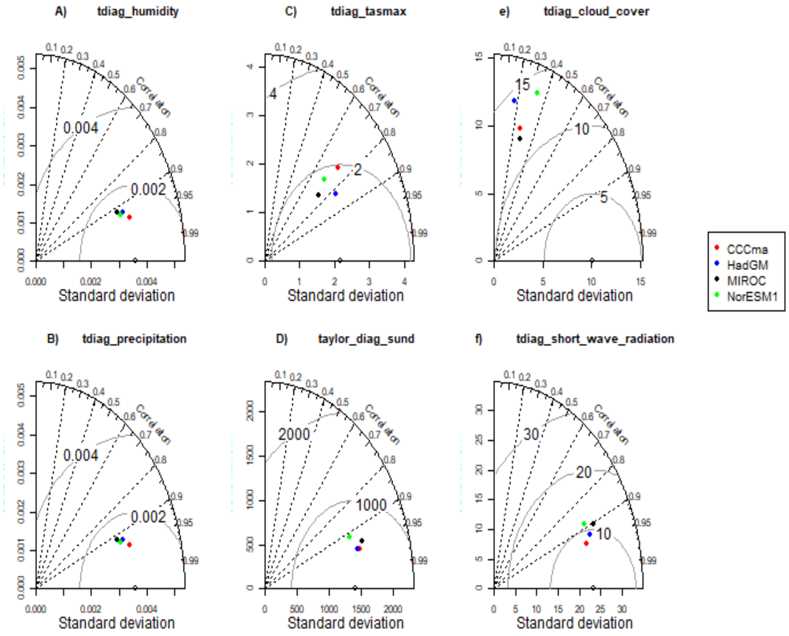


Figure 31: Taylor diagrams with statistics comparing models' simulations with reference dataset

2. Quantification of climate change effects on energy potentials.

2. 1 Climate impact on Climate variables

The projected changes for the energy parameters concerning the 4 models, the scenarios RCP 4.5 and 8.5 for the analysed variables (sund, pr, clt, rdsd, tasmax, sfwind) are presented in this section. The section present projections divided into two periods considered as mid and far future periods: 2015-2060 and 2061-299. No bias correction has been done on the models.

a. clt (total cloud fraction)

Figure 32 represents the future projected changes in the Total Cloud Fraction (clt) for the scenarios RCPs 4.5 and 8.5 under the period of 2015–2060, referred to as the mid-future. The projection presents a general decrease over the country under both scenarios RCP4.5 and RCP8.5, respective of the simulations both scenarios agree with a significant decrease in the total cloud cover over the study area. Depending on the models, these projected changes are significant. These results confirm the findings of a decrease in cloud cover (clt) of Sawadogo et al., (2021b). The models show a very large disagreement about the projected changes. CCCma-CanESM2 projects a general decrease in the near and the far future for both scenarios (RCP 4.5 and RCP 8.5), an average of 10% to 12% decrease in the near future and about 15% and 18% for the far future, while MIROC-MIROC5 projects a general increase (1.52% and 2.92%), MOHC-HadGEM2-ES (1.06%, 2.07), and NCC-NorESM1-M (1.15%,2.40%). Furthermore, the examination of Figure 31 reveals that, under both emission scenarios, the projected changes are more prominent for the far future than for the near future. The general observation is a discrepancy in the projected changes over the country. It is important to mention that the projected decrease is more prominent for RCP8.5 and 4.5 and significant for both time slices.

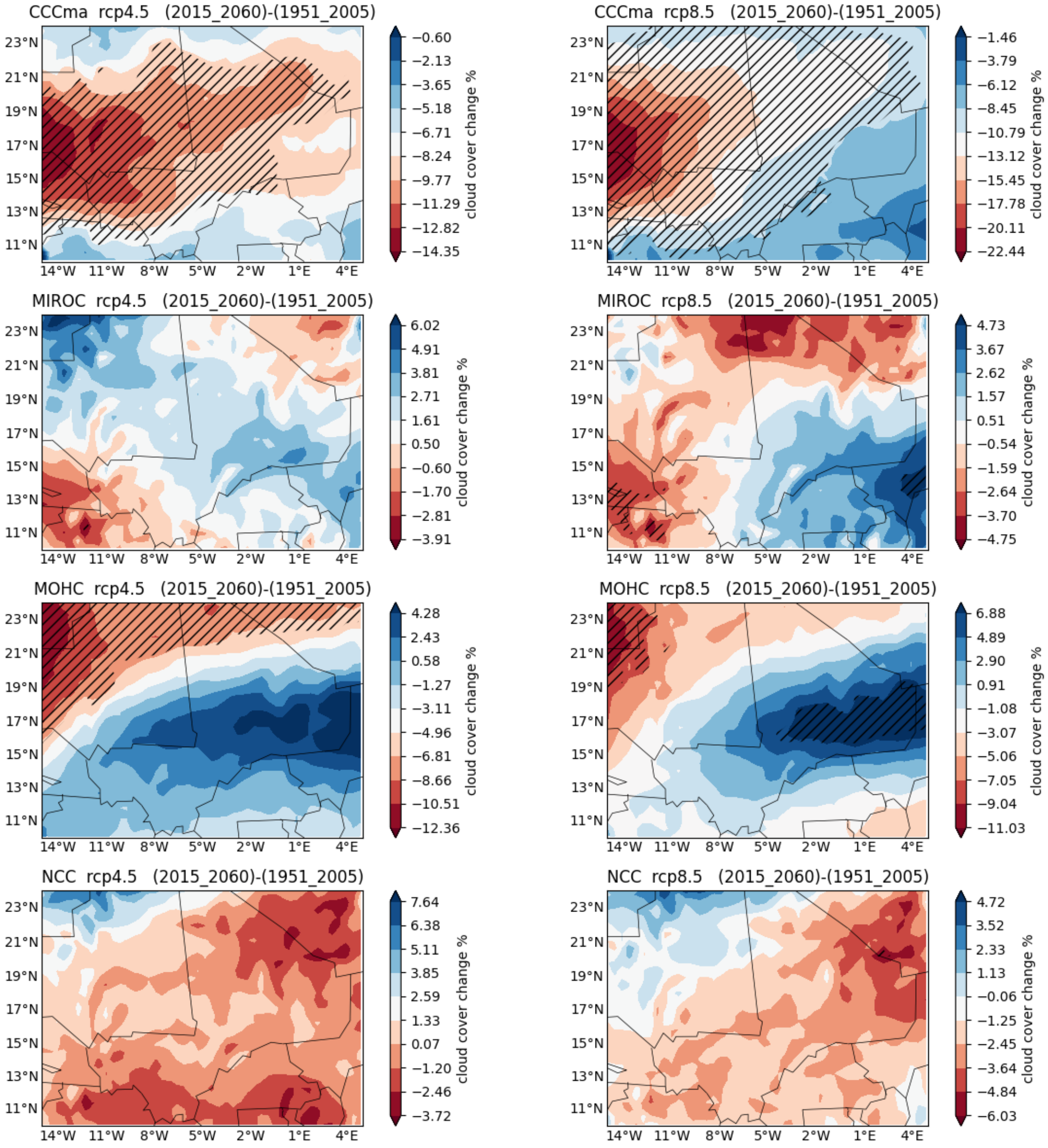


Figure 32: Projected changes in clt (Total CloudFraction), over Mali under the RCP4.5 and 8.5 for the timeline period of 2015-2060 for GCM-RCMS: CCCma-CanESM2, MOHC-HadGEM2-ES, MIROC-MIROC5, NCC-NorESM1-M

Figure 33 represents the projected changes of Total Cloud Fraction (clt) under scenarios RCPs 4.5 and 8.5 for the time period of 2061–2099 referred to as the far future, for the four assessed GCMs (CCCma-CanESM2, MOHC-HadGEM2-ES, MIROC-MIROC5, and NCC-NorESM1-M). Like the near future projections, the far future projection indicates a general decrease of the cloud cover across the study area in the far future period and for both study scenarios (RCP 4.5 and RCP 8.5). The models project an average of 10% to 12% decrease in the near future and about 15% to 18% for the far future CCCma-CanESM2, while MIROC-MIROC5 projects a general decrease (1.52% to 2.92), MOHC-HadGEM2-ES (1.06% to 2.07%), and NCC-NorESM1-M (1.15% to

2.40%). All four models agreed with the decrease in cloud cover, particularly in the southern part of the country. The GCM simulations exhibit agreement in the direction and magnitude of decrease, with change being more prominent for RCP8.5 than RCP4.5 for the near future. The changes are significant and more important with CCCma-CanESM2 for both Scenarios and with all other analysed models for only the scenario RCP8.5. Statistically significant areas are indicated by the bars. These findings are in line with those of *(Sawadogo et al., 2021).*

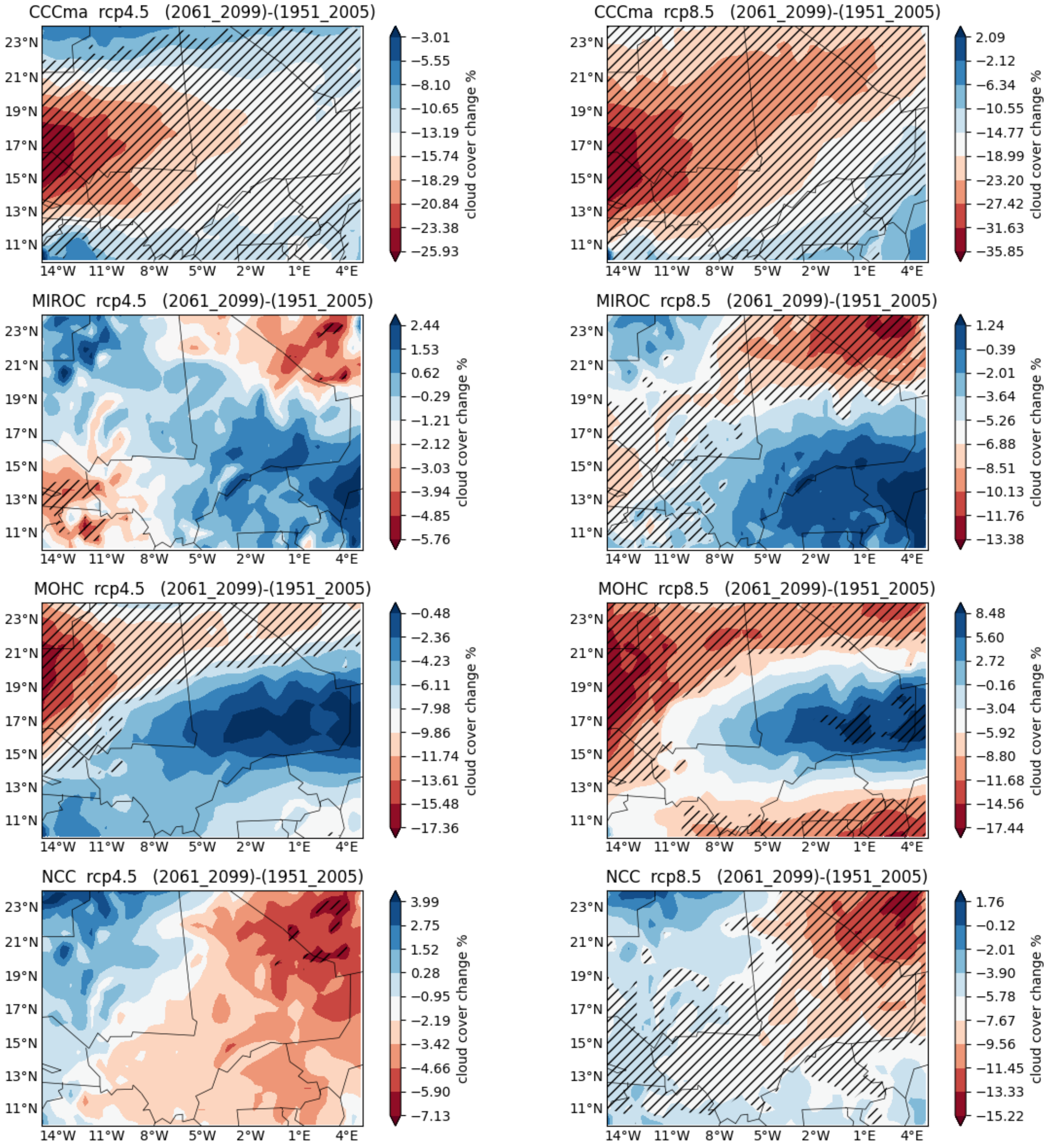


Figure 33: Projected changes in clt (Total CloudFraction), over Mali under the RCP4.5 and 8.5 for the timeline period of 2061-2099 for GCM-RCMS: CCCma-CanESM2, MOHC-HadGEM2-ES, MIROC-MIROC5, NCC-NorESM1-M

b. Near-Surface Wind Speed (sfcWind)

Figure 34 represents the projected changes for sfcWind (near-surface wind speed) under the scenarios RCPs 4.5 and 8.5 in consideration of the period of 2015–2060 mid-future. The projections indicate a slight increase in sfcWind (near-surface wind speed) over the study area. The projected changes range from 3 % to 5%, with CCCma-CanESM2 from 4% to 5%, MIROC-MIROC5 for MOHC-HadGEM2-ES (2%), and NCC-NorESM1-M (3% to 4%), for both scenarios RCP4.5 and RCP8.5, respectively, and for the near future 2015–2060 period. However, a decrease in the northern part of the study areas has been identified with the projections the decrease is more important relative to the various GCMs. It is worth mentioning that the changes do not exhibit significance for this period except for some small parts of the study areas with the model MIRROC for both RCPs and the model NCC for RCP 4.5. The changes are slightly significant around the northern areas with the Models Mirroc and the NCC. The finding is consistent with the finding of *(Sawadogo and al.,2019; Bichet et al.,2019).*

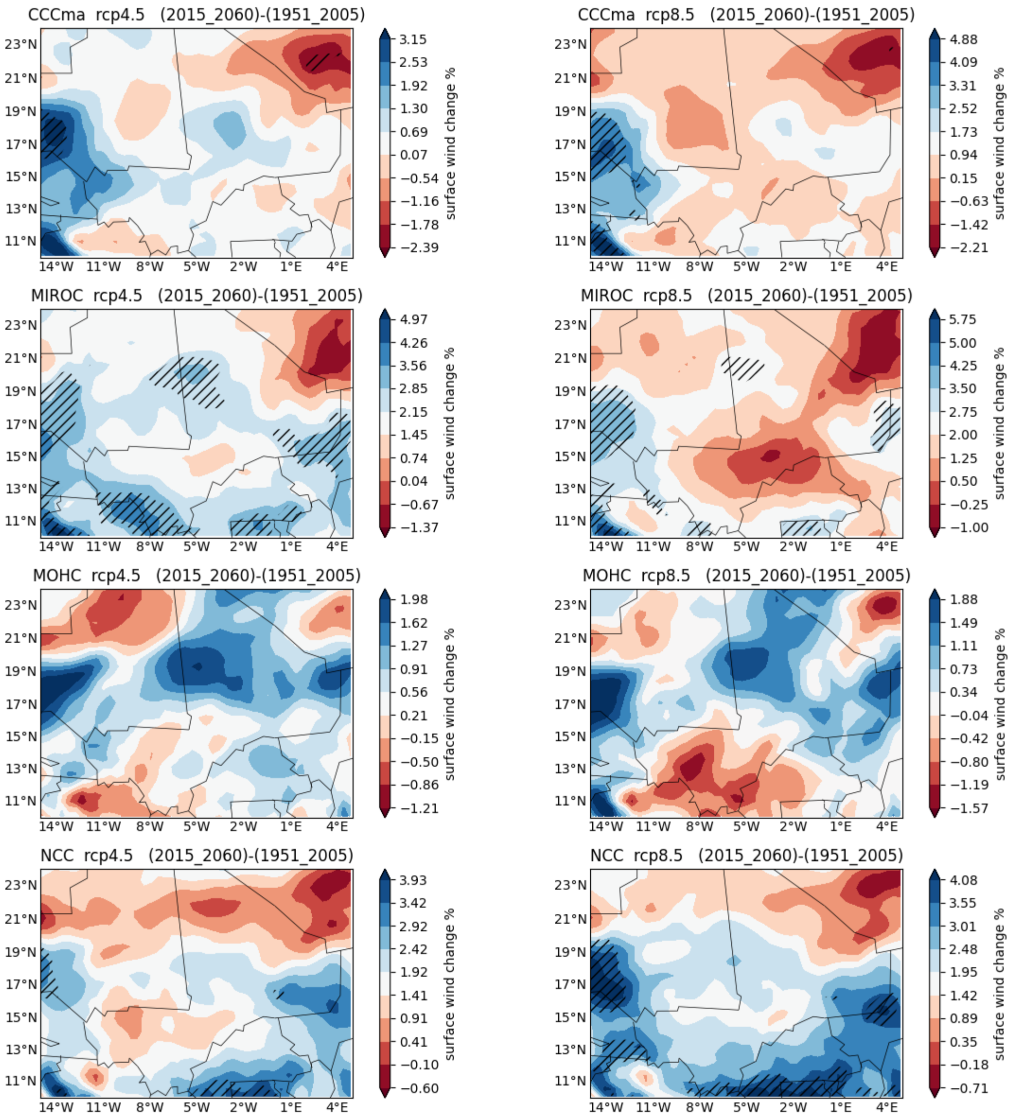


Figure 34: Projected changes in surface Wind (sfcWind), over Mali under the RCP4.5 and 8.5 for the timeline period of 2015-2060 for GCM-RCMS: CCCma-CanESM2, MOHC-HadGEM2-ES, MIROC-MIROC5, NCC-NorESM1-M

Figure 35 represents the projected changes for sfcWind (near-surface wind speed) under the scenarios RCPs 4.5 and 8.5 in consideration of the period of 2061–2099 in the future. All analysed GCMs agree on a general increase of the near surface wind speed potential. The increase ranges from CCCma-CanESM2 (4% to 10%), MIROC-MIROC5 (5% to 10%), MOHC-HadGEM2-ES (3% to 6%), and NCC-NorESM1-M (4% to 6%) for both scenarios respectively RCP4.5 and RCP8.5. The simulations show agreement about the projected changes in direction. MIROC-MIROC5 and NCC-NorESM1-M exhibit larger, more spread, and more significant changes (5% to 9%) in the sfcWind (near-surface wind speed) potentials. Additionally, it is worth mentioning that projected changes do not exhibit very much significance except for the far future for the Model MIROC-MIROC5 for both scenarios and for NCC-NorESM1-M for RCP8.5. These findings are in line with the findings of this study *(Sawadogo et al., 2019; Ndiaye et al., 2022; Sawadogo et al., 2021).*

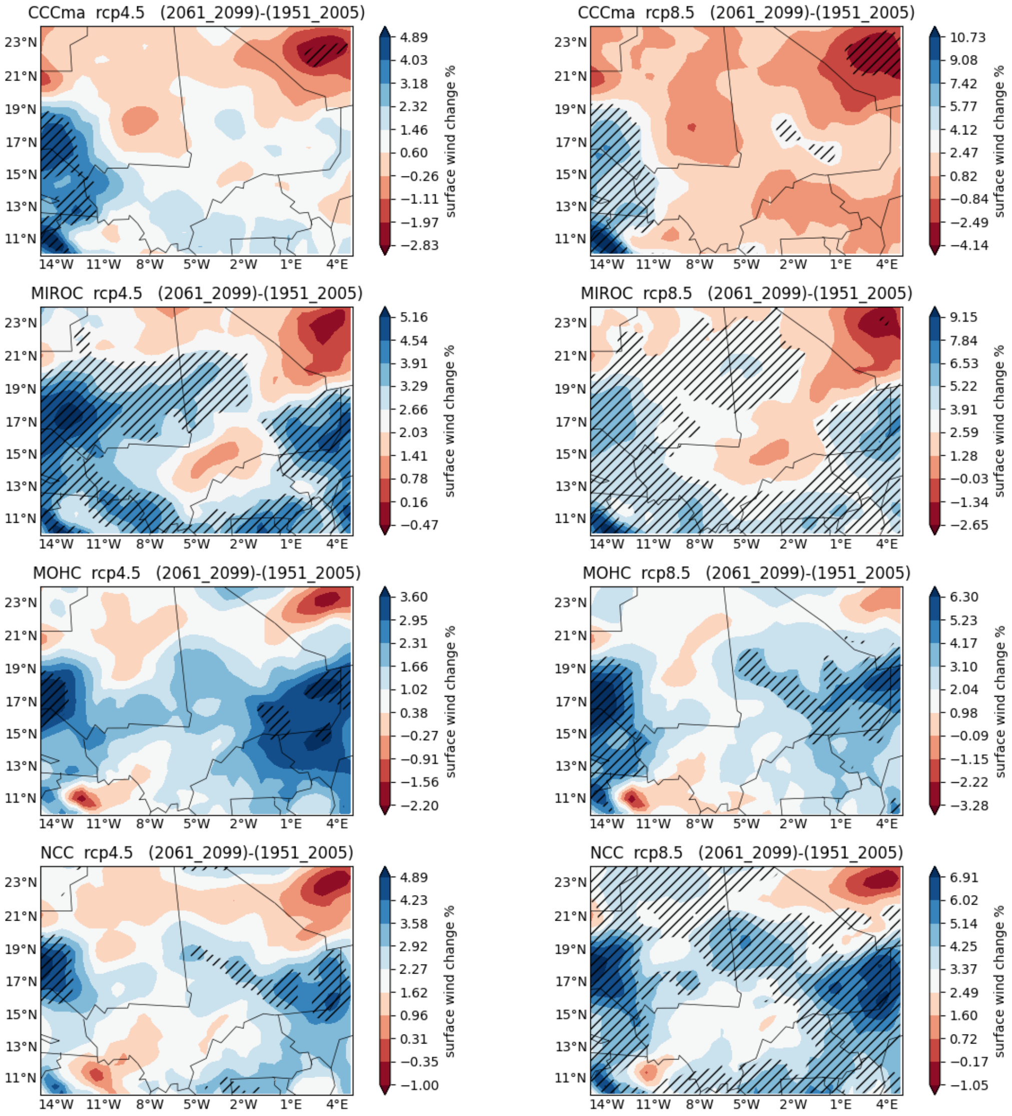


Figure 35: Projected changes in surface Wind (sfcWind), over Mali under the RCP4.5 and 8.5 for the timeline period of 2061-2099 for GCM-RCMS: CCCma-CanESM2, MOHC-HadGEM2-ES, MIROC-MIROC5, NCC-NorESM1-M

c. Surface Downwelling Shortwave Radiation (rsds)

Figure 36 represents the projected changes for rsds (Surface Downwelling Shortwave Radiation) for the scenario RCPs 4.5, and RCPs 8.5 under the time period of 2015-2060 mid-future. In the near future 2015-2060 for both greenhouse gas emission scenarios, the simulations projected a general decrease over the study area. All the models agreed with this potential decrease of the short-wave radiation over the south-eastern part of the country. However, the degree of agreement between models on the forecast (the predictions' robustness) varies slightly. Additionally, there is a slight similarity in the magnitude of increase in the projection: CCCma-CanESM2(~1.1 to 1.48%), MIROC-MIROC5(~1.52 to and 1.35), MOHC-HadGEM2-ES (0.80%,1.05), NCC-NorESM1-M (~0.96%,1.30%) for rcp4.5 et 8.5 respectively with significant change in the south East with CCCma-CanESM2 and MIROC-MIROC5 for RCPs8.5. This projected decrease is slightly more pronounced for the representative scenario 8.5 than for RCP4.5. The projected changes of surface Downwelling Shortwave Radiation agree with the projected decrease in *(Bazyomo et al.,2016; Bichet et al, 2019; Danso et al., 2022; Soares et al., 2019).* And conversely the finding is in opposition of the study (*Sawadogo et al.,2019).*

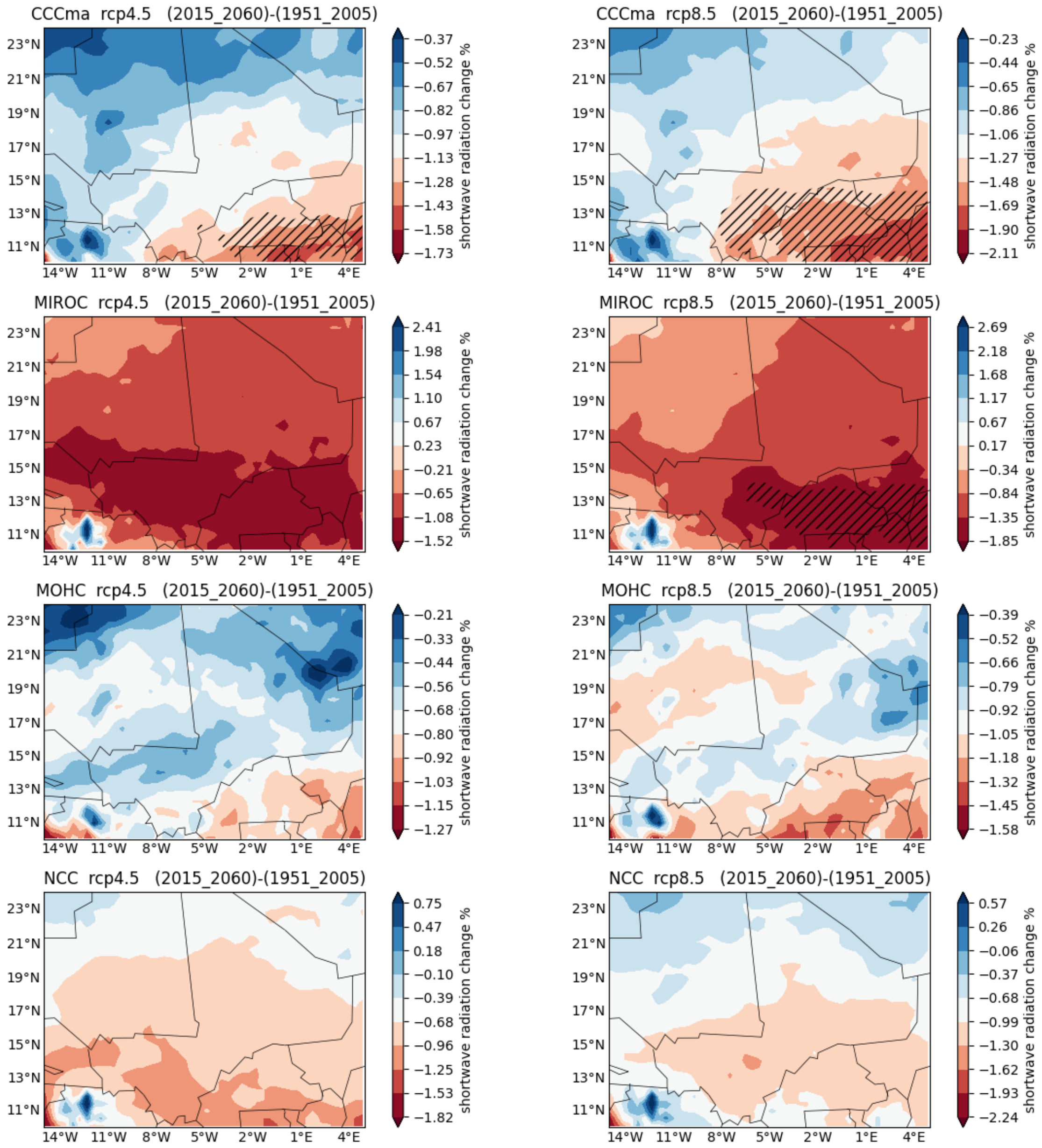


Figure 36: Projected changes rsds (Surface Downwelling Shortwave Radiation), over Mali under the RCP4.5 and 8.5 for the timeline period of 2015-2060 for GCM-RCMS: CCCma-CanESM2, MOHC-HadGEM2-ES, MIROC-MIROC5, NCC-NorESM1-M

The projected future changes for rsds (surface downwelling shortwave radiation) for the scenarios RCPs 4.5 and 8.5 under the period of 2061–2099 far-future here represented by Figure 37. For both greenhouse gas emission scenarios, the simulations project a general potential decrease over the study area in agreement with near future projections. All the models agreed on an important short-wave radiation decrease over the southeast of the country. However, the degree of agreement between models on the forecast (the predictions’ robustness) varies slightly. The magnitude of increase is more important for RCP8.5 than for RCP 4.5 from the models respectively CCCma-CanESM2 (1.13%, 1.48%), MIROC-MIROC5(1.52% and 1.35), MOHC-HadGEM2-ES (0.80%, 1.05), and NCC-NorESM1-M (0.96%, 1.30%), with a significant change in the south-east identified with CCCma-CanESM2 and MIROC-MIROC5 for RCPs 8.5. This decrease is more pronounced for the representative scenario RCP 8.5 than for RCP4.5 and also more significant in the far future period than for near future and reciprocally por for both scenarios (Fig. CCCma-CanESM2(1.8%, 3.19%), MIROC-MIROC5(1.52%), MOHC-HadGEM2-ES (1.06%, 2.07), and NCC-NorESM1-M (1.15%, 2.40%) for RCP4.5 and RCP 8.5, respectively. These findings are in composition with the findings of Sawadogo et., (2021) *(Sawadogo et al., 2021)* which find an increase in the variable over west Africa where the study area is located.

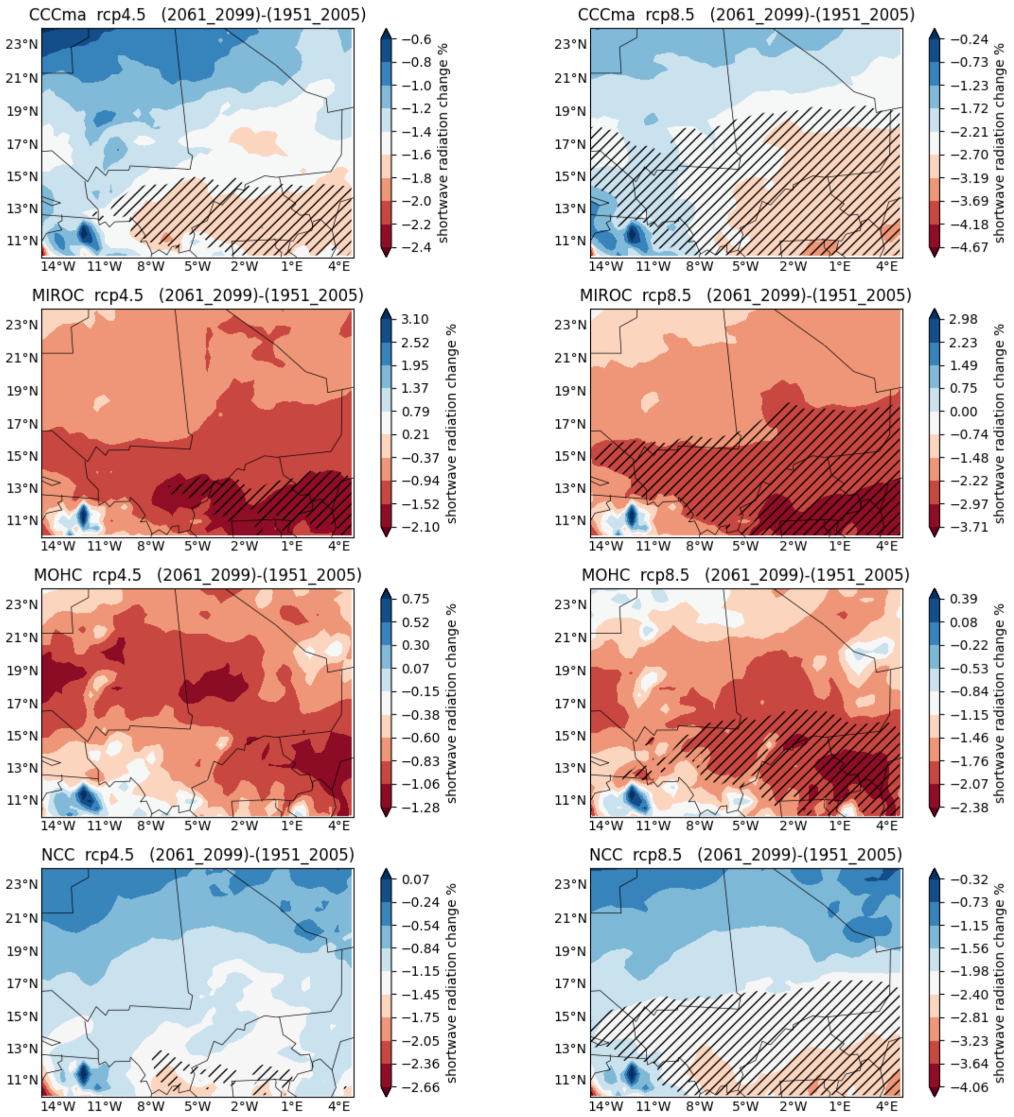


Figure 37: Projected changes rsds (Surface Downwelling Shortwave Radiation), over Mali under the RCP4.5 and 8.5 for the timeline period of 2061-2099 for GCM-RCMS: CCCma-CanESM2, MOHC-HadGEM2-ES, MIROC-MIROC5, NCC-NorESM1-M

d. Precipitation (pr)

Figure 38 represents the projected changes for precipitation (pr) for the scenarios RCPs 4.5 and 8.5 over the period of 2015–2060 near-future. The precipitation changes projected by the models show an increase ranging from (15% to 20) CCCma-CanESM2, MOHC-HadGEM2-ES, MIROC-MIROC5, NCC-NorESM1-M vary positively from the southern towards the northern parts of the study area. Under both representative concentration scenarios RCP4.5 and RCP8.2, the simulation projects a severe and significant increase in precipitation of about 20%, specifically important and significant in the southern part for MIROC-MIROC5. This increase is significant and uniform with all four GCMs and with both scenarios in agreement with the model CCCma-CanESM2, MIROC-MIROC5, in considering near period time slice projection 2015–2060. The projected increases are consistent with the finding *(Diallo et al., 2012)* which the study assumed to be a consequence of could cover reductions. It is also consistent with the *(Engelbrecht et al., 2015)* who attribute this to the near surface temperature increase.

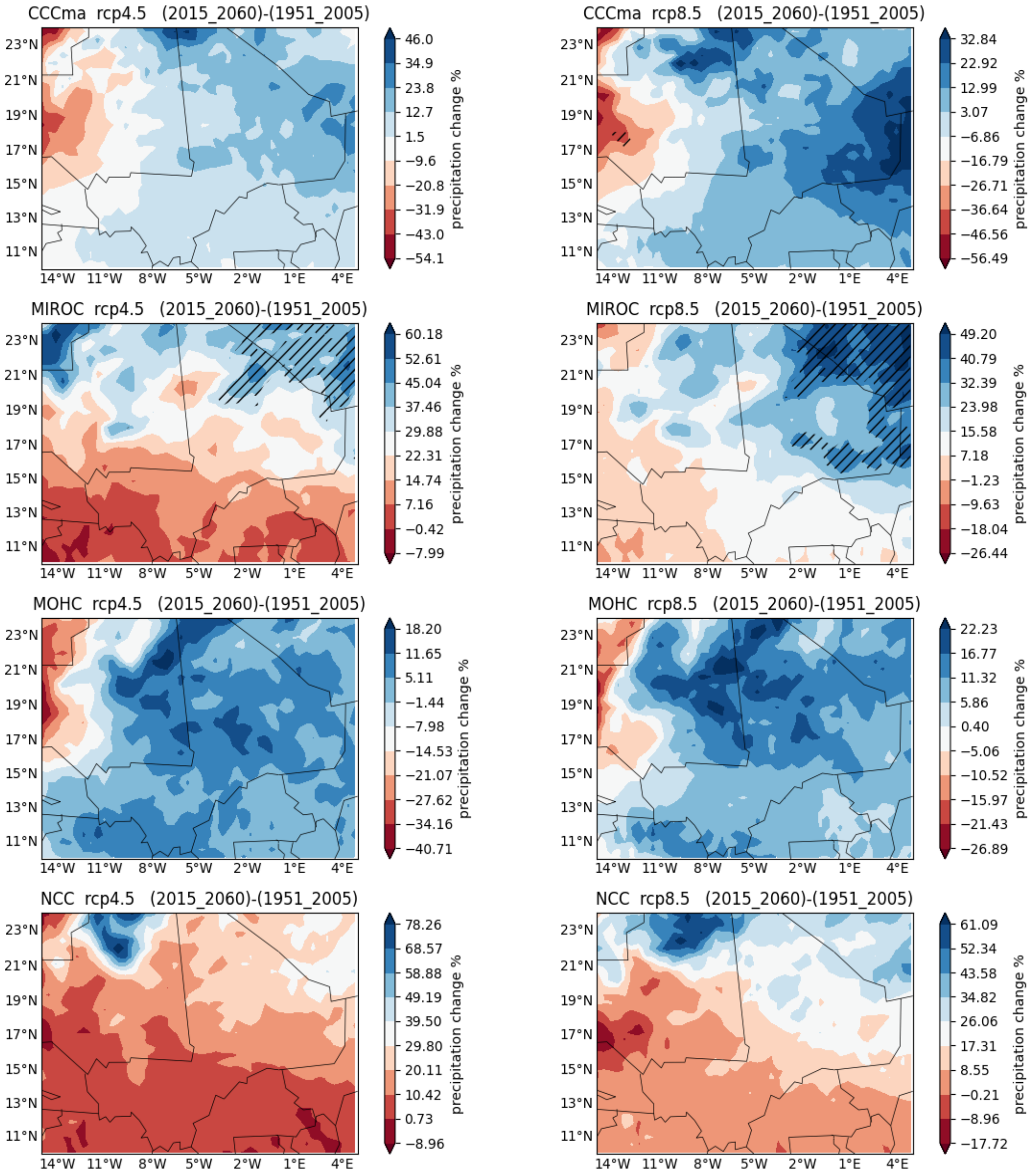


Figure 38: Projected changes in surface precipitation (pr), over Mali under the RCP4.5 and 8.5 for the timeline period of 2015-2060 for GCM-RCMS: CCCma-CanESM2, MOHC-HadGEM2-ES, MIROC-MIROC, NCC-NorESM1-M

Figure 39 represents the projected changes in Precipitation (pr) for the scenario RCPs 4.5, and RCPs 8.5 under the time period of 2061-2099 considered as far-future. Projected future changes identified with the various analysed GCMs under and the identified times slices are presented here. The GCMs project an increasing trend of the precipitation

Changes of the different RCPs, and are statistically significantly represented with transverse bears, especially for RCP8.5. The analysed GCMs project an increasing and significant trend under both RCPs for 2061–2099 for both RCP4.5 and RCP8.5. The simulation projects a general and significant increase of precipitation of about 15% more or less with individual RCMs; the increase is more important in the northern part than in the southern part of the study areas. The potential increase is located in the northern part of the country with a more important increase observed with MOHC-HadGEM2-ES 20 % in RCP 4.5 2061-2099 and with both time slices for RCP8.5. And the more severe increase in the projections is identified with CCCma-CanESM2 and RCP8.5. The least precipitation increase is identified with the MOHC-HadGEM2-ES model.

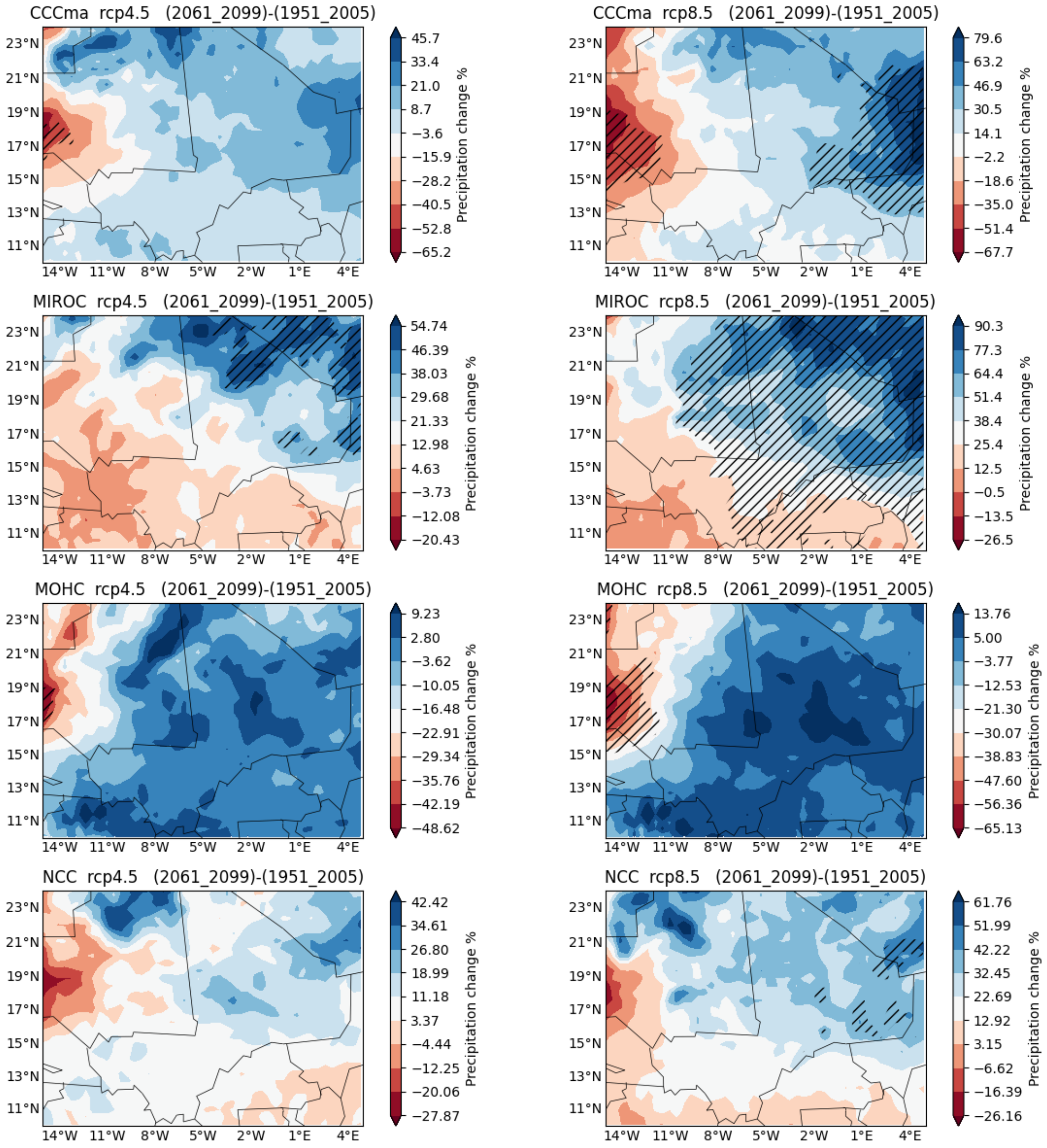


Figure 39: Projected changes in precipitation (pr), over Mali under the RCP4.5 and 8.5 for the timeline period of 2061-2099 for GCM-RCMS: CCCma-CanESM2, MOHC-HadGEM2-ES, MIROC-MIROC5, NCC-NorESM1-M

e. Daily Maximum Near-Surface Air Temperature (Tasmax)

Figure 40 represents the projected changes for Tasmax (Daily Maximum Near-Surface Air Temperature) for the scenario RCPs 4.5, and RCPs 8.5 under the time period of 2015-2060 near-future and 2061-2099. The projections show an increase of the tasmax for both scenarios and for both the near and long-term future. The projected increase in temperature is more pronounced in the far future than in the near future. CCCma-CanESM2(~0.63%, 0.83%), MIROC-MIROC5(~0.59% and 0.67%), MOHC-HadGEM2-ES (0.69%,0.84%), NCC-NorESM1-M (~0.64%,0.65%) for near future

2015-2060 with respectively RCPs4.5 and 8.5 CCCma-CanESM2(~1.03%, 1.63%), MIROC-MIROC5(~0.59%, 1.51%), MOHC-HadGEM2-ES (0.66%,1.91%), NCC-NorESM1-M (~0.54%,1.32%) in far future projections for RCPs4.5 and 8.5 respectively. The highest temperatures located in the Northern part of the country above 16 °N and identified the MOHC-HadGEM2-ES (0.84%) near future and MOHC-HadGEM2-ES (1.91%) far future for the scenario RCPs8.5. These changes are significant at 95% with all the simulations and across the country. This increase in temperature is more prominent in the far future than in the near future with magnitude varying or in change in both periods and with both scenarios. However, it is also worth mentioning that the magnitude of the changes varies according to the GCMs relative to the scenarios and the periods in both periods. The increase in Surfaces air Temperature over the study areas and the African region is also confirmed and in agreement with the temperature increase indicated by *(Sawadogo et al., 2021; Diallo et al., 2012., Bichet et al., 2019 ; Engelbrecht et al., 2015)*

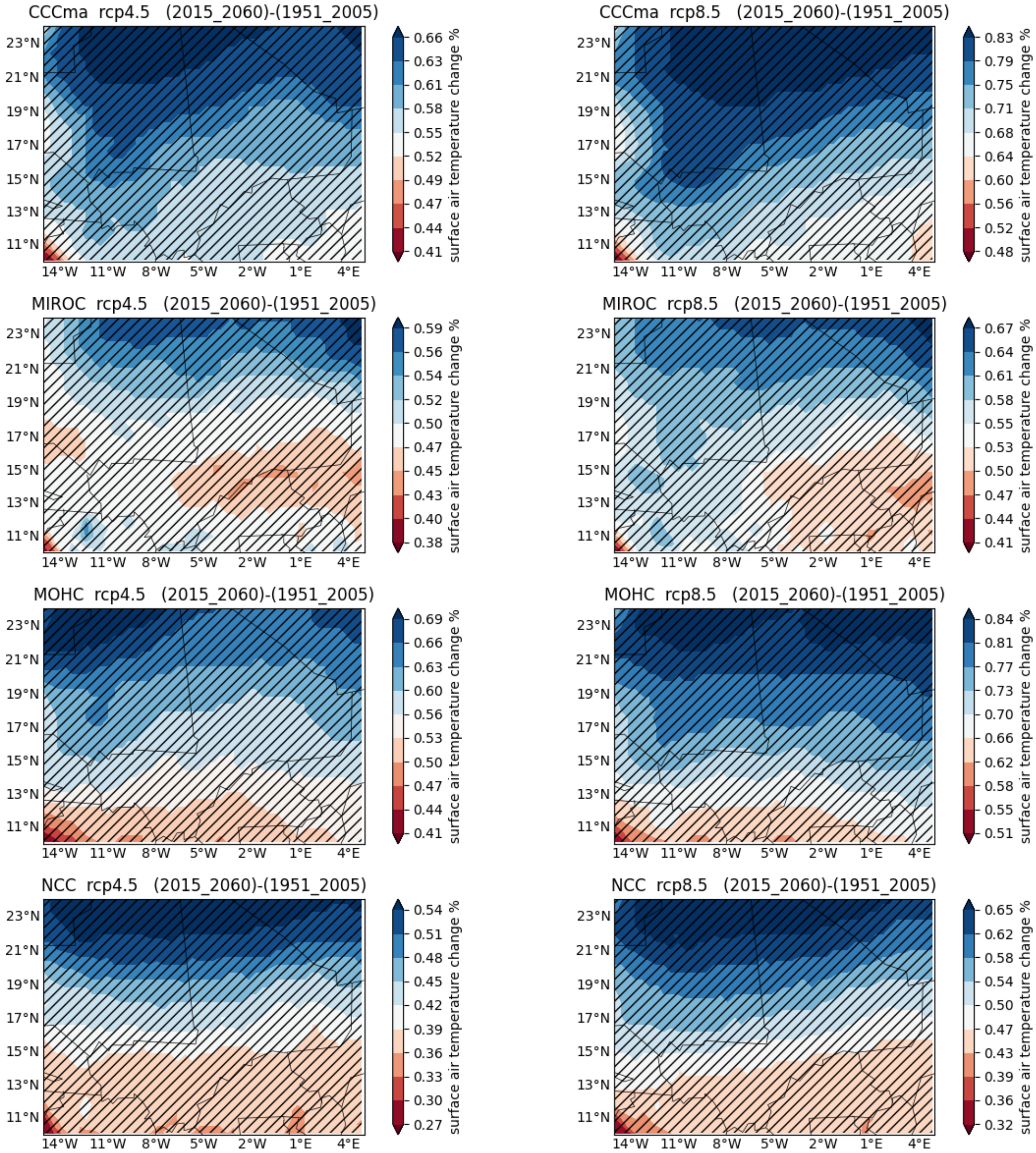


Figure 40: Projected changes in Tasmax (Daily Maximum Near-Surface Air Temperature), over Mali under the RCP4.5 and 8.5 for the timeline period of 2015-2060 for GCM-RCMS CCCma-CanESM2, MOHC-HadGEM2-ES, MIROC-MIROC5, NCC-NorESM1-M

Figure 41 represents the projected changes for Tasmax (Daily Maximum Near-Surface Air Temperature) for the scenario RCPs 4.5, and RCPs 8.5 under the time period of 2015-2060 near-future and 2061-2099. The projections show an increase of the tasmax for both scenarios and for both the near and long-term future. The projected increase in temperature is more prominent in the far future than in the near future with magnitude varying of in change in both periods and with both scenarios CCCma-CanESM2(~0.63%, 0.83%), MIROC-MIROC (~0.59% and 0.67%), MOHC-HadGEM2-ES (0.69%,0.84%), NCC-NorESM1-M (~0.64%,0.65%) for near future 2015-2060 with respectively

RCPs4.5 and 8.5 CCCma-CanESM2(~1.03% , 1.63%), MIROC-MIROC5(~0.59% and 1.51%), MOHC-HadGEM2-ES (0.66%,1.91%), NCC-NorESM1-M (~0.54%,1.32%) in far future projections for RCPs4.5 and 8.5 respectively. The highest temperatures are located in the Northern part of the country above 16 °N and identified with the MOHC-HadGEM2-ES (0.84%) near future and MOHC-HadGEM2-ES (1.91%) far future for the scenario RCPs8.5. These changes are significant with all the simulations and across the country. Surface air Temperature general increase of the simulation is consistent with the finding of *(Sawadogo et al., 2021)* and similarly with the finding of *(Bazyomo et al., 2016; Bichet et al., 2019 ; Soares et al., 2019)*

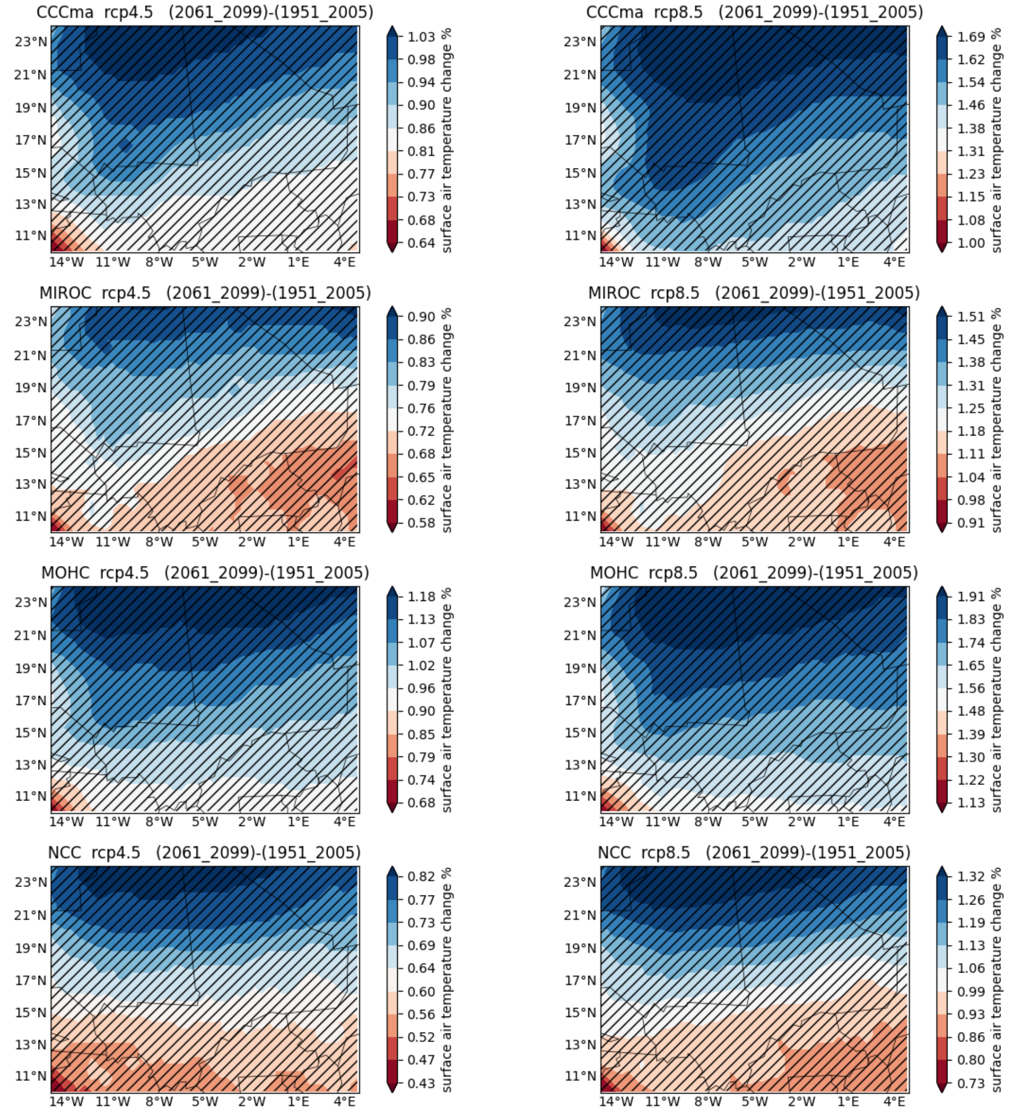


Figure 41: Projected changes in Tasmax (Daily Maximum Near-Surface Air Temperature), over Mali under the RCP4.5 and 8.5 for the timeline period of 2061-2099 for GCM-RCMs: CCCma-CanESM2, MOHC-HadGEM2-ES, MIROC-MIROC5, NCC-NorESM1-M

A decrease in cloud cover is an indication of surface air temperature increase which will lead to an increase in the potential of solar production *(Gaetani et al., 2014). T*his could also lead to an increase in energy demand in general and colling energy requirements in particular. An increase in cloud cover thus leads to renewable energy production decrease. The implementation of several of the previously analysed energy sustainability scenarios particularly those with significant energy share of renewable energy resources would be challenging.

Wind speed changes directly influence the stability of wind energy production *(Ravestein et al., 2018; Wang et al., 2020)*, thus the identified increase projections with wind speed would positively impact wind production in the study areas. The projected potential increase of wind speed would thus positively impact by increasing energy production from renewable energy resources.

The identified increase trend of the precipitation is set to increase hydropower production. The identified increase in surface temperature will have a negative effect on solar energy production and affect the cell efficiency *(Gaetani et al., 2014)*, it is also set to increase the effect of evapotranspiration decreasing the potential for hydropower production *(Jaffe et al., 2019; Wang et al., 2020; Zhao et al., 2022).* This would negatively impact renewable energy production *(Sawadogo et al., 2021).*

The projected changes identified with energy parameters would influence the implementation of the different scenarios according to the nature of the change projected with a magnitude relative to the share of renewable resources share in the scenario.

The projected changes will primarily affect the technical dimension of energy supply meaning: TCH1: Production Efficiency, TCH2: Capacity Factor, TCH3: Resources potential, TCH4: Reliability of the system, TCH5: Resources availability. It also affects environmental dimension aspect of energy supply: ENV1: Energy Diversification, ENV2 Fraction of Renewable Energy, ENV3: Land Use and Rate of Deforestation (M2/Mwh), ENV4: Emission (Gco2e/Kwh) increasing the negative economical aspect of energy supply as well as affecting the social dimension of energy supply.

The scenarios will respond to identified decreases /increases depending on the share of renewable energy in the scenario.

The higher the share of renewable energy resources in the scenario the higher the system is positively/negatively (relative to the projection) impacted. This highlights the complex nature of implementation of these scenarios for long term energy supply sustainability.

Hence, the importance of MCDM in to integrating the various dimensions of sustainability.in order to identify the ideal and suitable scenario to be implemented for long term sustainable energy supply.

2.2 Climate impact on energy potentials

Results for the projected change energy potential are presented in this section.

a. Projected changes in Photovoltaic power output (PVP)

Figure 42 shows projected future changes in photovoltaic energy potential (PVP) for both scenario RCP4.5 and RCP8.5 and for both time slice 2015-2060 near future and 2061-2099 far-future. All the GCMs project a decrease of the PVP energy output in the southern part and an increase in the Northern part. For the near-term period projection all the GCMs projects a clear increase of about 2% of the solar potation over Mali in the exception of the Model MIROC-MIROC5 which exhibits a decrease of about 1% of the potential in the southern part of the country. The reduction can reach 1% in the southern part of the country. The increase can reach 2.5% in the northern part of the study areas (see figure 42)**.** However, the magnitude of the changes varies according to the GCM in both periods. It is worth mentioning that none of the GCMs project a significant change for neither of the representative concentration scenarios analyses which is in contradiction with the study of (Bichet et al., 2019) . where the projections predict a decrease of about 4% over Africa. Higher temperatures reduce the efficiency of the PV cells and the lower irradiance will lead to lower PV energy *(Danso et al., 2022)* It is indicated that an increase in total cloud cover can also significantly decrease solar radiation thus decreasing the production of solar energy power *(Danso et al., 2020; 2022.)* The present study finds a decrease in cloud cover, a decrease in rsds a decrease in tasmax and an increase in the Humidity, hence is in line with the findings of these studies and in line with the identified increase in the solar energy production projection. The projected increase in solar radiation is also confirmed by *(Danso et al., 2022).*

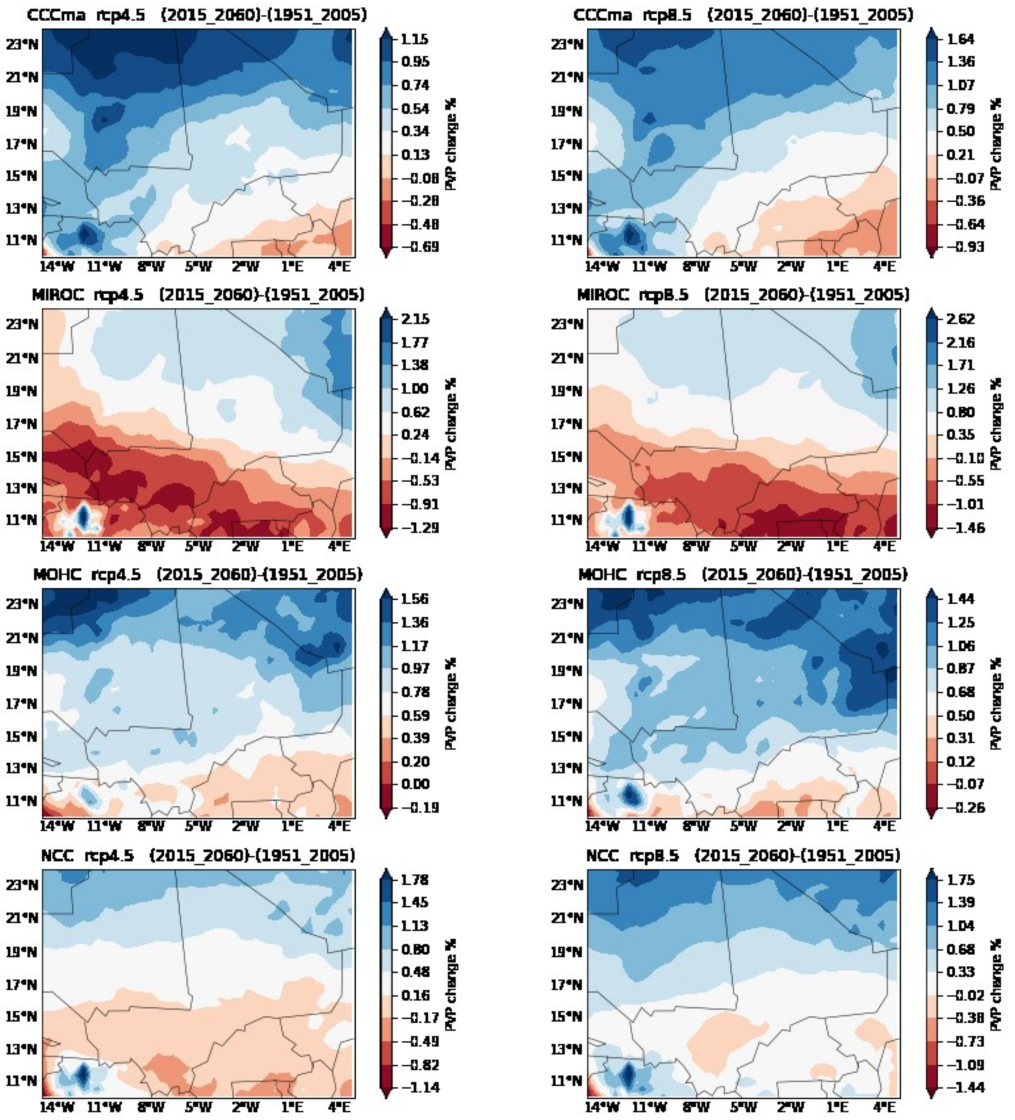
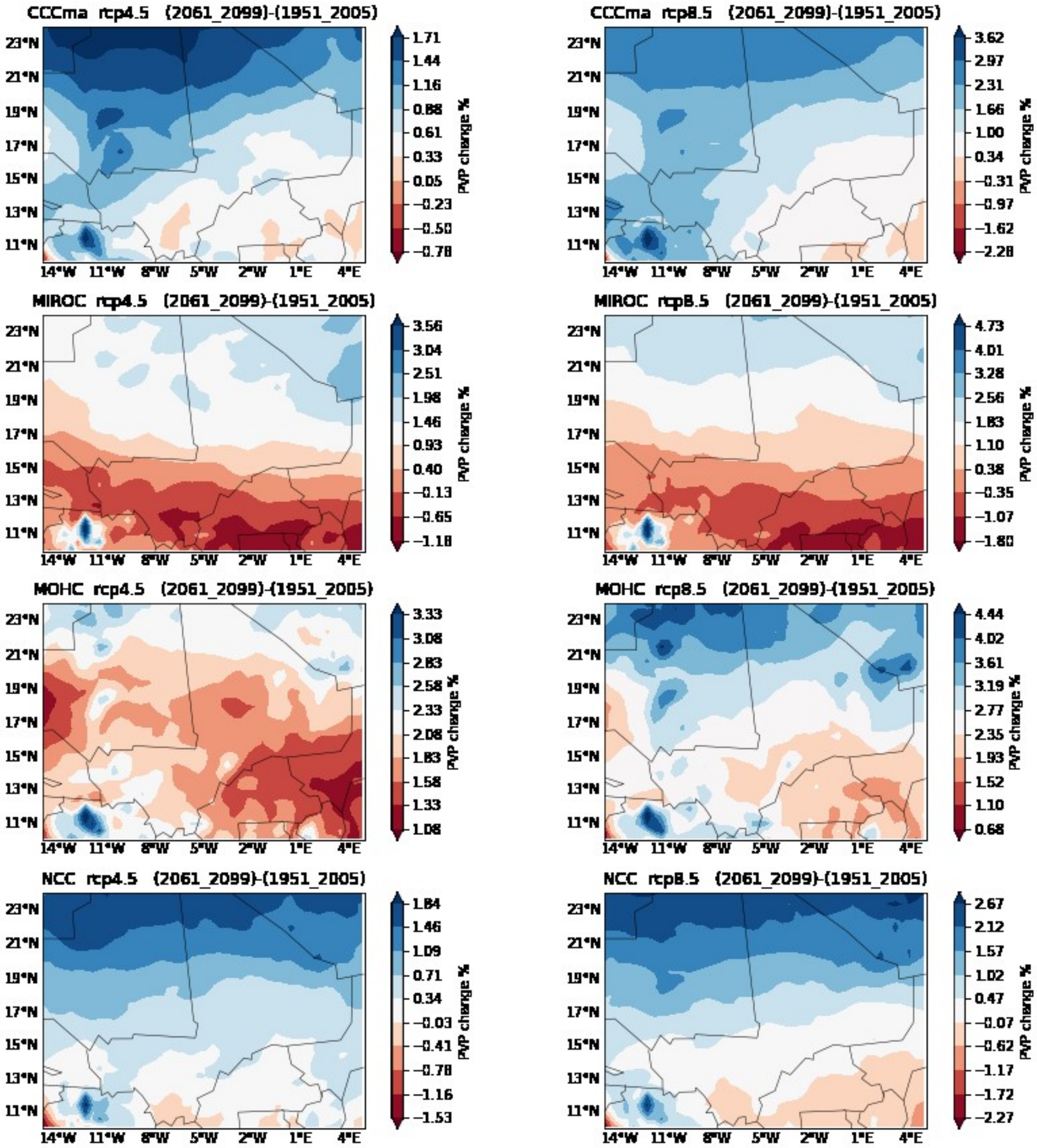


Figure 42: Photovoltaic power output (PVP) changes over Mali under the RCP4.5 and 8.5 for the timeline period of 2015-2060 for GCM-RCMS: CCCma-CanESM2, MOHC-HadGEM2-ES, MIROC-MIROC5, NCC-NorESM1-M

A decrease in PVP potential is however identified with MIROC-MIROC5 especially in the southern part of the study area The projected decrease of the solar energy is projected confirmed with *(Danso et al., 2022; Bazyomo et al., 2016; Bichet et al., 2019).* The difference in the magnitude of projected changes can be attributed to the different GCMs and the various representative concentration scenarios used with the studies.

In confirmation with the far near future the projection an increasing PVP potential has been identified with the far future 2061-2099 with a higher magnitude. The identified increase is in the order of about 5% (see figure 43). It is however worth mentioning that all the models agree with this increase except for MIROC-MIROC5 which indicates a decrease in PVP potential in the southern part of the country. For both representative concentration RCP4.5 and rcp8.5 and both periods in the near and far future. PVP projection is highly dependent on the projected changes in those variables (short radiation, the temperature and wind speed). PV power output decreasing is cause by increasing in surface temperature and the solar irradiance affecting the temperature of the PV cell namely Tcel confirmed by *(Bazyomo et al., 2016)* which also highlights that PV output decreases with increasing temperatures in its study.



CCCma rcp4.5 (2061_2099)-(1951_2005)

CCCma rcp8.5 (2061_2099)-(1951_2005)

MIROC rcp4.5 (2061_2099)-(1951_2005)

MIROC rcp8.5 (2061_2099)-(1951_2005)

MOHC rcp4.5 (2061_2099)-(1951_2005)

MOHC rcp8.5 (2061_2099)-(1951_2005)

NCC rcp4.5 (2061_2099)-(1951_2005)

NCC rcp8.5 (2061_2099)-(1951_2005)

Figure 43: Photovoltaic power output (PVP) in over Mali under the RCP4.5 and 8.5 for the timeline period of 2015-2060 for GCM-RCMS: CCCma-CanESM2, MOHC-HadGEM2-ES, MIROC-MIROC5, NCC-NorESM1-M

b. Projected changes in Wind power density

Figure (44) represents the changes for the near future 2015-2060 for both representative concentration scenarios and for all four GCMs. The projected potential for wind power density is characterised by an increase with the model CCCma-CanESM2 with both RCPs for the first time slice. The increases are in the order of 1-5% for an increase observed with RCP8.5 which has higher magnitude compared to RCP4.5 in all simulations of Wind power density in Mali. The models have relatively higher magnitude of changes the highest being observed with NCC-NorESM1-M and. It is important to highlight the high disparity between the simulation MOHC-HadGEM2-ES and the others which located the increases in southern part for NCC-NorESM1-M of the study areas. These findings are with the result of *(Sawadogo et al., 2021;Sawadogo et al., 2019*).

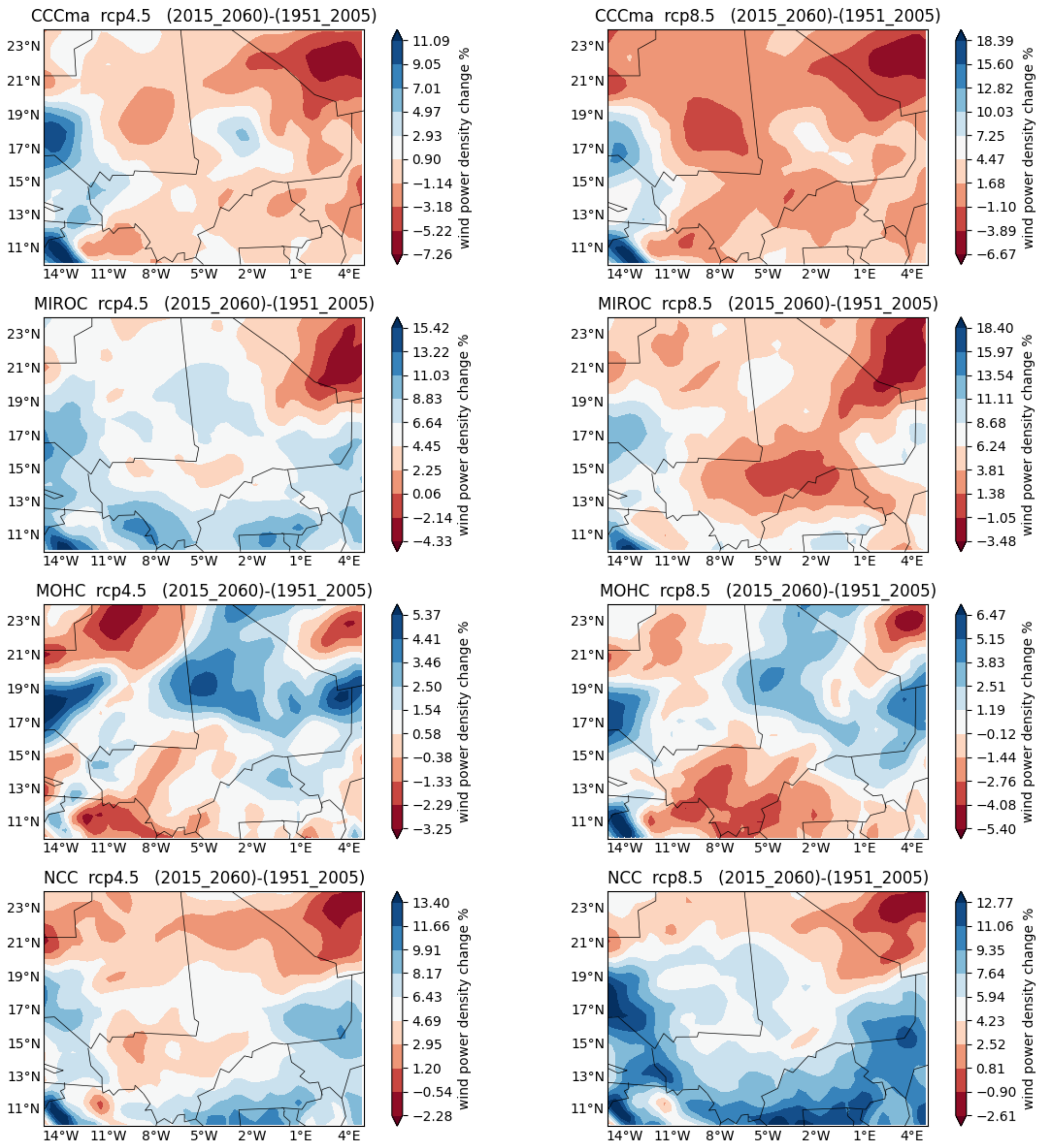
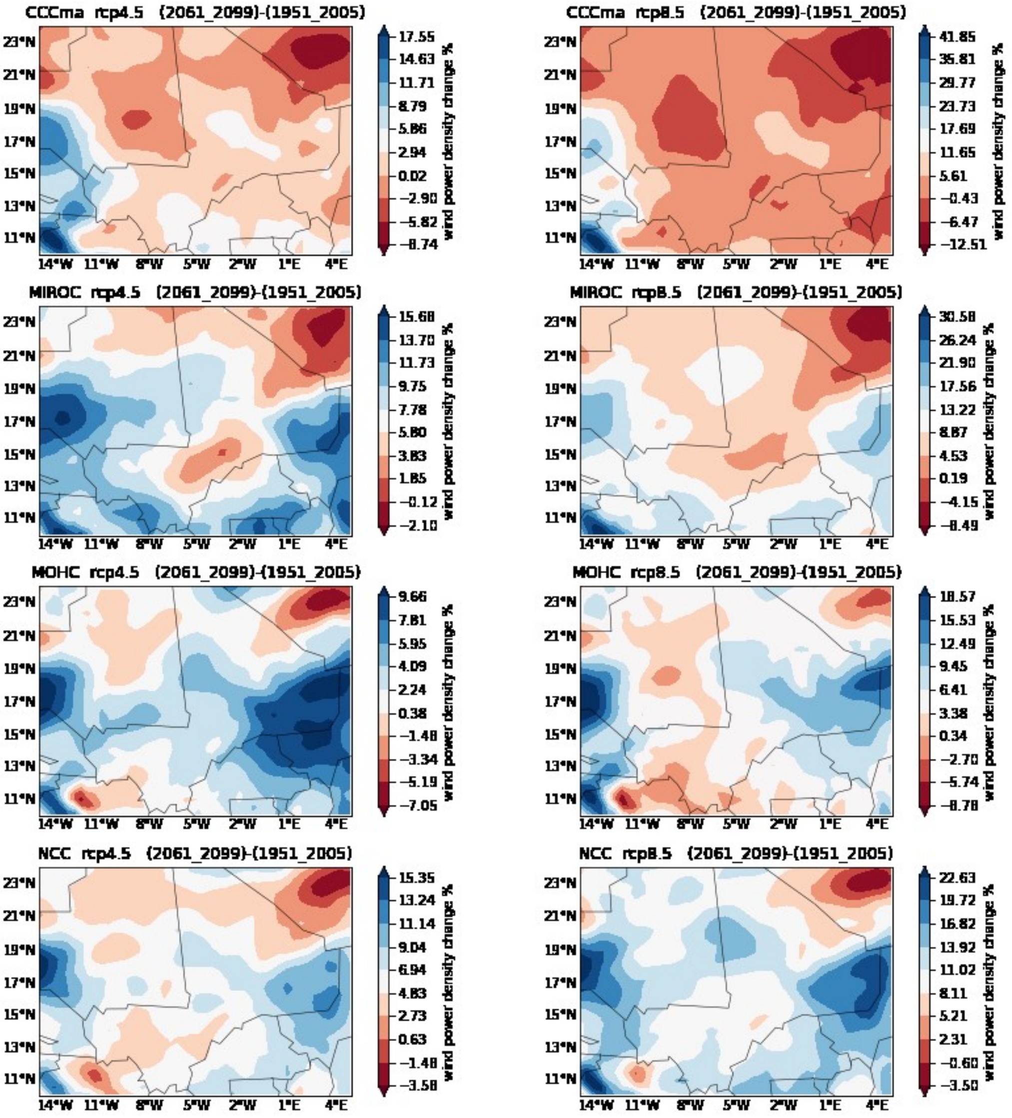


Figure 44: Projected changes in Wind power density over Mali under the RCP4.5 and 8.5 for the timeline period of 2015-2060 for GCM-RCMS: CCCma-CanESM2, MOHC-HadGEM2-ES, MIROC-*MIROC5, NCC-NorESM1-M*

Figure 45 represents the projected changes in wind power density for the far future 2061-2099 for both representative concentration scenarios and for all four GCMs. The projections of the far future 2061-2099 are in line with those of the near future where the increases are more prominent. The changes exhibited by the different GCMs are not significant. The magnitude of the increase is important relative to the GCMs. CCCma-CanESM2 projects the highest increase which gets higher from RCP4.5 to RCP8.5. The projected changes in WPD exhibit a consistent pattern for both RCPs with different magnitudes. It is worth mentioning that for the far future, all the analysed GCMs agree with the direction of changes. *(Sawadogo et al., 2021)*


CCCma rcp4.5 (2061_2099)-(1951_2005)

CCCma rcp8.5 (2061_2099)-(1951_2005)

MIROC rcp4.5 (2061_2099)-(1951_2005)

MIROC rcp8.5 (2061_2099)-(1951_2005)

MOHC rcp4.5 (2061_2099)-(1951_2005)

MOHC rcp8.5 (2061_2099)-(1951_2005)

NCC rcp4.5 (2061_2099)-(1951_2005)

NCC rcp8.5 (2061_2099)-(1951_2005)

Figure 45: Projected changes in Wind power density over Mali under the RCP4.5 and 8.5 for the timeline period of 2061-2099 for GCM-RCMS: CCCma-CanESM2, MOHC-HadGEM2-ES, MIROC-MIROC5, NCC-NorESM1-M

The success of various pledges (the nationally determined contribution, especially the greenhouse gas emission reduction of 31%, the Paris agreement, the united nation sustainable development goal and climate change) depends on the future climate change impact on energy systems (the solar PV generation depends on climate variables like temperature and solar irradiance *(Sawadogo et al., 2021).* In sum, to achieve these objectives, there is a need for reliable and accurate information on the potential impacts of climate change on energy systems (renewable energy resources and others). The finding of the study highlights renewable energy resources as a viable pathway for future supply of sustainable energy for all in Mali. It outlines the need for expanding energy access and electricity production through hydropower, interconnections, and other renewable and local energy resources, while reducing reliance on thermal energy. Among the various energy supply pathways, Scenario 4 emerging as the most socially and environmentally sustainable, and Scenario 3 aligning closely with Mali's NDC goals of reducing GHG emissions by 31% by 2030. The findings identify renewable energy, particularly solar PV and wind energy, as sustainable options for future energy planning in Mali. Strong and supportive policies and investment in renewable technologies is key for the successful supply of sustainable energy for all and meeting the commitment of the NDCs. On the other hand, clear caution must be places on these energy resources in link with climate change impact and variabilities on these

.

Chapter VI: General Conclusions et Recommendations

General Conclusions:

This study investigated potential impacts of climate change on the Malian energy supply sustainability considering the country Nationally determined contributions (NDCs) using MCDM approaches and climate model analysis under the RCP4.5 and RCP8.5 climate change scenarios in order to better understand the potential future changes on energy related variables (temperature, sunshine duration wind,) that are bound to affect the energy production and supply systems such as PVP potential, wind energy potential and hydropower over Mali. The study provides insights on the current state of the Malian energy supply, its vulnerability, and dependencies, additionally it also presents the future sustainability issues that the systems could face and provide pathways and guidance for the future sustainable energy system planning.

Five different energy supply alternatives and the BAU developed above were submitted to the assessment. The approach presented in this study aimed to support long-term energy planning decision-making, especially in the context of climate change. The sustainability assessment technique considered indicators distributed among four dimensions: technical (5), social (5), economic (6), and environmental (4), adopted based on energy stakeholders' survey, the priority choice of energy stakeholders has shown a preference for the economic and technical dimensions with respectively 41% and 39 % of the average weights for sustainable energy planning in Mali. Thus, the social and environmental dimensions have been given less weight with 11% and 9% respectively.

Scenario 3, the transition towards renewable energy technologies (petroleum product: 29%, renewable energy: 42%, biomass: 27%, and energy import: 2%), ranks as the best option for sustainable energy supply in Mali. This scenario, considering the input of Malian energy stakeholders, favour economic and technical aspects in the planning of sustainable energy supply. The identified supply alternative constitutes the most diversified with a significant share of renewable energy. The lowest sustainability score is found for scenario 5 (petroleum products: 40%, renewable energy: 33%, biomass: 10%, and energy imports: 17%) which raises the problem of energy supply dependency on a high share of petroleum products and the energy import.

The approach for sustainable energy planning put forward is intended to educate decision-makers on numerous options for defining and shaping national energy strategies that fulfil important commitments of Mali.

Renewable energy resources: wind, Solar, hydro, and biomass have been shown to have particularly Been put forward as important resources for the country's energy sustainability. Future energy systems sustainably will significantly depend on the stability of these resources. However, these renewable energy resources are being particularly affected by climate change through the projected changes in the mean annual precipitation; wind speed, solar radiation (and all the other climate related energy variables). There is evidence that the changing climate poses significant sustainability challenges to countries energy supply, particularly for Mali energy supply which is based on renewable energy. Hence The right projection of climatic parameters and how renewable energy resources will be impacted by the changing climate will be of great importance in determining future sustainability of energy planning in Mali. Hence the following the findings of the present study are to be considered:

The projected changes observed with the assessed four GCMs and both Representative Concentration Representative (RCP) scenarios RCP4.5 and RCP8.5 for the four following simulations models: MIROC-MIROC5, NCC-NorESM1-M, CCCma-CanESM2. all the assessed variables including temperature patterns, altered precipitation regimes, and other climate energy-related variables have been set to have profound implications for the future energy production patterns. The findings indicate that all four analysed GCMs show a reasonable correlation with our observation data. Though, the models performed differently with different parameters and reproduced reasonably well the climatology of the country under the RCP4.5 and RCP8.5,

The GCMs identified an increase in solar energy production and an increase was also identified in the wind density potential and indicated an increase in wind production. Recognising the vulnerabilities, understanding the interdependencies, and embracing innovative solutions can help navigate the challenges of changing climate and pave the way for a more sustainable and secure energy future for our nation. Hence this study serves as a call to action. It is important to have the right information on how climate change will impact the resources for proper future energy planning. Hence the continuous investigation of climate change impact assessment requires accurate and solid information from the climate models.

The study showed the ways and means that the country's energy supply system could be sustainable by using scenario analysis and applying multi-criteria decision-making. Additionally, the findings could be helpful to Mali and other developing and developed countries in providing a consistent pathway for sustainable energy planning. It provides government tools to establish new energy policies and guidelines and adjust old policies and strategies in order to help the country to meet the international pledges (Nationally determined contributions (NDCs)) and achieve the Sustainable Development Goals SDGs particularly goal 7 access to clean and affordable energy for all, goal 11 goal 15 and etc.

The findings from this study revealed the importance of using a multi-criteria decision-making approach when assessing energy sustainability and dealing with the multifaceted aspect of energy sustainability, including the comprehensive evaluation of technical, economic, environmental, and social aspects of energy supply. Additionally, the research shed light on the need to consider the impacts of climate change on energy systems, as this will greatly influence the future sustainability of these systems. By understanding and addressing these challenges, we can work towards creating more sustainable energy systems that can effectively mitigate climate change and ensure a brighter future for generations to come.

Additionally, the findings also highlight that collaboration among stakeholder's government agencies, industry players, research institutions, and local communities is essential in crafting sustainable energy pathways forward. The findings of this study provide a foundation for informed decision-making, offering insights that can guide the development of climate-resilient energy strategies. In sum, it provides a comprehensive examination of the complex relationship between climate change and the sustainability of a country's energy supply and the importance of using multicriteria decision making in order to consider every aspect of complex long term energy planning. The findings highlight the urgent need for proactive measures to address the multifaceted impacts of climate change on energy infrastructure, availability, and resilience.

The current work updates the lists of literature on the assessment of the Mali energy supply systems *(Gazull et al., 2019; Sessa et al., 2021)* and presents literature on the use of the MCDM method of assessment, which gives energy stakeholders a tool to make more accurate decisions about the future energy supply for the sub-region.

Recommendations:

In the face of these highlighted challenges encountered by the country's energy system, the present study points to the following opportunities for innovation and adaptation for the future energy planning. The following recommendations are to be considered in enhancing future energy supply systems' sustainability and the various international policies about sustainable development goals (SDGs) especially 7-11- and 15 and the Paris Agreement particularly considering climate changes and order energy sector related challenges.

To researchers and academics

- Link climate knowledge with actions, and persuade businesses, communities, and individuals to adjust their behaviour in ways that promote adaptation and limit emissions.
- Exploit opportunities in energy and water-saving and the nexus, the demand-side management measures that could provide cost-effectiveness, solutions for mitigation and adaptation and help build resilience and sustainable energy solutions in the context of rising demand and supply constraints.

To policy/ decision makers:

- Adapting to variations in building energy demand and other demand increases will help reduce energy demand (especially) for cooling.
- Climate resilience, and climate change adaptation also need to be integrated into energy planning and decision-making processes at all relevant levels. Equally, energy sector responses to climate change need to be considered in the broader development context.
- Integrate climate resilience considerations into energy policies is paramount to ensuring sustained access to affordable, reliable, and clean energy supply systems
- Future energy planning should consider the updated national energy strategies climate solution, local energy and renewable energy resources, the increasing urban energy demand.

The interconnectedness of climate change impacts renewable energy resources and it links with other economic sectors, emphasising the ripple effects across the entire energy ecosystem. As one sector experiences disruption, the cascading effects on others become apparent. This interconnectedness necessitates an integrated and holistic approach to energy planning and policy formulation, acknowledging that no facet of the energy supply chain operates in isolation.

To investors:

- Investing in a more decentralised energy structure based on locally available renewable energy sources located in secure locations would reduce the probability of large-scale outages when centralised power systems are compromised.
- Energy efficiency, storage solutions to mitigate intermittency in renewable sources, and strategic diversification are crucial components to resilient and sustainable energy. Energy storage technologies and energy saving practices are to be considered.

Perspectives:

The results of this study can help governments and policymakers in targeting RES for future projects as part of the energy transition for climate change mitigation by considering the impacts of climate change on these resources. In order the improve the finding future work can consider:

- Bias correction impact on the accuracy of the findings.
- Analysing other RCMs projections and compare to the RCA4 used in the current work.
- Using the projection for other RCPs (2.6 and 6.0)
- Consider using the climate projection using the Shared Socio-economic Pathways (SSPs) scenarios.
- Consider using an integrated assessment model (IAM) to evaluate the country future energy supply sustainability.
- A better resolution dataset to avoid the uncertainties in the climate projections.

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Appendices

Appendice 1: Form used in stakeholder Survey for weighting dimensions and indicators

a. *Assign percentages to these dimensions (sum should be 100%) based on priority for sustainable supply of energy in Mali*

Dimension	**percentage**
Technical aspect	…………………………………
Economic aspect	…………………………………
Social aspect	…………………………………
Environmental aspect	…………………………………

b. *Give a score over 10 to indicators of the technical dimension based on priority for sustainable supply of energy in Mali*

Technical Indicators	**score**
TCH1: Production Efficiency (%)	…………………………………
TCH2: Capacity Factor (%)	…………………………………
TCH3: Resources potential (MW)	…………………………………
TCH4: Reliability of the system (Qualitative)	…………………………………
TCH5: Resources availability (Toe)	…………………………………

c. *Give a score over 10 to indicators of the economic dimension based on priority for sustainable supply of energy in Mali*

Economical Indicators	**score**
ECO1: net import dependency	………………………………
ECO2: Fuel cost	………………………………
ECO3: Levelized cost of electricity	………………………………
ECO4: Investment cost	………………………………
ECO5: Payback period.	………………………………
ECO6: Government support	………………………………

d. *Give a score over 10 to factors of the social dimension based on priority for sustainable supply of energy in Mali*

Social Indicators	**score**
SCO1: Energy acceptability	………………………………
SCO2: Energy accessibility	………………………………
SCO3: Job creation	………………………………
SCO4: Energy Affordability	………………………………

SCO5: People displacement	………………………………

e. *Give a score over 10 to the factors of the environmental dimension based on priority for sustainable supply of energy in Mali*

Environmental Indicators	**score**
ENV1: Energy diversification	………………………………
ENV2: Fraction of renewable energy	………………………………
ENV3: Land demand/ Rate of deforestation	………………………………
ENV4: Emission and Global warming potential	………………………………

Appendice2: National Malian institutions involved in the energy sector

Institution	Key task	Remarks
Ministère de l'Energie et de l'Eau	Responsible for policy formulation, promotion, co-ordination, monitoring and evaluation	Main structures : Direction Nationale de l'Énergie ; Direction Nationale de l'Hydraulique
Agence Malienne pour l'Energie Domestique et l'Electrification Rurale	Responsable for rural electrification	Off-grid energy service provider, regulating generation systems below 250 kilowatts
Agence des Energies Renouvelables du Mali	Promotes widespread use of renewable energy in the country to enable sustainable socio-economic development	Created from a redefinition of the mandate of the former National Center for Solar and Renewable Energy
Agence Nationale de Développement des Biocarburants	Formulates and implements national biofuels policy	Ensures the regulation of the bioenergy sub-sector
Commission de Régulation de l'Electricité et de l'Eau	Regulates electricity and water sectors	Independent from government operators, with juridical powers and financial autonomy. Under the supervision of the Prime Minister's Office.
Agence pour la promotion des investissements au Mali	One-stop shop for all procedures to setting up companies, assisting investors and issuing approvals relating to the Mali Investment Code	Its institutional footing changed in 2019 when it moved from the Ministry of Investment to the Prime Minister's Office
Agence de l'Environnement et du Développement Durable	Focuses on biodiversity preservation, fights against desertification and climate change Home	Home to the Mali Green Fund and a key player in the elaboration and implementation of the Nationally Determined Contribution

Appendice 3: Published article

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Sustainability Assessment of Energy Supply Scenarios: Case study of Mali

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Keywords: MCDM, energy supply, energy planning, sustainability assessment, Mali.

Abstract

Mali is endowed with significant untapped renewable energy potentials paradoxically the country is identified as an energy-poor nation characterized by very high dependency on imports of petroleum products and heavy reliance on biomass (wood-fuel and charcoal). Access to electricity remains very low, with significant disparities across urban and rural remote areas. The gap between the electricity demand and supply keeps increasing yearly, and power shortages get frequent and longer, especially during dry periods from March to June. The energy demand increase, due to population growth and rapid urbanization (causing more use of fossil fuels resources in the energy mix) bears the unsustainability of the country's current energy supply. The challenge for the country is then to meet this growing energy demand with a sustainable energy supply system. In the present work, Analytical Hierarchy Process technique is applied to perform Multicriteria Decision Making analysis to identify and assess the most sustainable long-term energy supply options in Mali considering technical, environmental, social, and economic dimensions. The current situation and five alternatives of energy supply based on the country's current and future energy supply and climate change policies are proposed for assessment. Results show that the highest priority indicators by stakeholders' survey are under economical dimension followed by the technical ones. The best scenario considers deploying renewable energy to up to 42% of the energy mix as the sustainable option for energy supply. Adopting such a scenario requires measures such as a strong political will to subsidize renewable energy equipment in order to make them affordable and also policies that encourage the use of renewable energy (such as lower taxes and duties). The

suggested framework gives decision-makers, authorities, practitioners, and researches an effective tool for the country future energy planning