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Renewable energy production under climate change, decentralized smart grid and sustainable energy system: Evidence in Togo

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Dedication :

This dissertation is dedicated to:

■ My wife: **Rita A. Amega**, and

■ Children: **Rioniel E. K. Amega** and **Ossan G. Amega**,

for their immense understanding, love, support and patience during my field work,
my scientific visit to Cologne, data analysis and write-up stages of this thesis document.

Abstract :

West African countries' power sector encounters interrelated problems, such as intermittent power access, lack of power security and reliability, aging distribution infrastructure, and the impact of climate change. To meet their increasing energy demand and ensure a secure and reliable electricity supply under the changing climate, a resilient sustainable energy system is to be developed and promoted. Accordingly, the current research seeks to create an enabling environment that will permit the development of a sustainable electric power system model that is climate-resilient and compatible with the Togolese power system. This case study enables energy security through energy efficiency promotion, clean energy development, supply quality and reliability improvement, and reduction of greenhouse gases (GHG) by increasing electricity access in Togo. To reach the objectives of the study, an integrated approach is used. Firstly, Sandia method-assessment approach is applied to develop a typical meteorological year (TMY) as an alternative solution for data issues in renewable energy (RE) studies. Secondly, the impact of changing climate (CC) on decentralized power resources (solar energy) technology and generation potential has been conducted based on energy rating and photovoltaic cell (monocrystalline, polycrystalline and amorphous) temperature models at the national level under RCP2.6 and 8.5 scenarios. Finally, the existing power system networks are thoroughly investigated based on expert elicitation and modelled with Simscape-MATLAB/Simulink in view of a Smart Grid (SG) development considering the penetration of renewable energy (RE). Results showed a very low installed RE (hydro and solar) capacity of 11.27% from 2015 to 2020. The generated TMY predicts PV system performance within 2% of the datasets at all sites. Regarding the impact of CC, PV cells' temperature would likely rise across all five regions in the country and may trigger a decline in the PV potential under RCP2.6 and 8.5. However, the magnitude of the induced change depended on two major factors: (1) PV technology and (2) geographical position. These dissimilarities were more pronounced under RCP8.5 with amorphous technology. The Togolese power sector is characterized by a number of issues including limited supply, technical issues regarding transmission and distribution (power losses due to aging infrastructures), and power outages. Therefore, the power system is modeled in view of its transformation to increase supply and improve reliability and resiliency.

Keywords: renewable energy, climate change impact, power supply system, modeling, Simscape.

Résumé :

Le secteur de l'électricité des pays d'Afrique de l'Ouest est confronté à des problèmes interdépendants tels que l'accès intermittent à l'électricité, le manque de sécurité et de fiabilité de l'électricité, le vieillissement des infrastructures de distribution et l'impact du changement climatique. Pour répondre à leur demande croissante en énergie et garantir une électricité sûre et fiable dans un contexte de changement climatique, un système énergétique durable et résilient doit être développé et promu. C'est dans cette perspective que la présente thèse a cherché à établir un environnement favorable à un modèle de système électrique durable résilient au changement climatique pour le système électrique togolais. Cette étude de cas permet d'assurer la sécurité énergétique par la promotion de l'efficacité énergétique, le développement des énergies propres, l'amélioration de la qualité et de la fiabilité de l'approvisionnement, et la réduction des gaz à effet de serre (GES) en augmentant l'accès à l'électricité au Togo. Pour atteindre les objectifs de l'étude, une approche intégrée est utilisée. Premièrement, l'approche d'évaluation de la méthode Sandia est appliquée pour développer une année météorologique typique (TMY) comme solution alternative aux problèmes d'accès aux données dans les études sur les énergies renouvelables (RE). Deuxièmement, l'impact du changement climatique (CC) sur la technologie et le potentiel de production des ressources énergétiques décentralisées (énergie solaire) a été mené sur la base de modèles de température des cellules photovoltaïques (monocristallines, polycristallines et amorphes) et d'évaluations énergétiques aux niveaux national et régional dans le cadre des scénarios RCP2.6 et 8.5. Enfin, les réseaux électriques existants ont fait l'objet d'une étude approfondie basée sur l'élucidation d'experts et ont été modélisés avec Simscape-Matlab/Simulink en vue du développement d'un réseau intelligent (Smart Grid, SG) tenant compte de la pénétration des énergies renouvelables (RE). Les résultats ont montré que jusqu'en 2020, la capacité installée des ER (hydro et solaire) était très faible (11,27 %). Le TMY généré prédit la performance du système PV à moins de 2% des ensembles de données dans tous les sites. En ce qui concerne l'impact du CC, la température des cellules PV augmenterait probablement dans les cinq régions du pays et pourrait déclencher un déclin du potentiel PV sous RCP2.6 et 8.5. Cependant, l'ampleur du changement induit dépend de deux facteurs principaux : (1) la technologie PV et (2) la position géographique. Ces dissimilitudes étaient plus prononcées sous RCP8.5 avec la technologie amorphe. Le secteur électrique togolais est caractérisé par un certain nombre de problèmes, notamment une offre limitée, des problèmes techniques concernant la transmission et la distribution (vieillesse des infrastructures, pertes d'électricité) et des pannes de courant. Par conséquent, le système électrique est modélisé en vue de sa transformation pour augmenter l'offre et améliorer la fiabilité et la résilience.

Mots clés : énergie renouvelable, impact du changement climatique, système d'alimentation électrique, modélisation, Simscape.

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II. The two submitted manuscripts have been mainly written by the doctoral candidate (first author). The respective co-authors (Saidou Madougou, Yendoubé Laré, Ramchandra Bhandari, Yacouba Moumouni, etc.) made inputs before submission to Journals.

III. The third empirical Chapter (4) is currently prepared in readiness for submission soon to a Journal.

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Abbreviations :

AC	Alternating current
ADB	African Development Bank
AIM	Advanced Infrastructure Metering
AMEA	Power Company
ARSE	Agence de Régulation du Secteur Electrique
a-Si	Amorphous
AT2ER	Agence Togolaise d'Electrification Rurale et des Energies Renouvelables
BBOXX	Power Company
BMBF	Federal Ministry of Education and Research of Germany
CAPEX	Capital expenditures
CC	Climate Change
CEB	Communauté Electrique du <i>Bénin</i>
CEET	Compagnie Energie Electrique du <i>Togo</i>
CIZO	which means "to light" in the local language "Guin".
CMIP5	Coupled Model Intercomparing Project—Phase 5
CORDEX- CORE	Coordinated Regional Climate Downscaling Experiment-Common Regional Experiment
DC	Direct current
DE	United States Department of Energy
DES	Decentralized Energy Source
DGE	Direction Générale de l'Energie
DRE	Decentralized Energy Resource
DRP-CCE	Doctoral Research Programme on Climate Change and Energy
DSM	Demand Side Management
ECMWF	European Centre for Medium-Range Weather Forecasts
ECOWAS	Economic Community of West African States
ECREEE	ECOWAS Centre for Renewable Energy and Energy Efficiency
EE	ENERGY Efficiency
EMS	Energy Management System
EPRI	Electric Power Research Institute
ERA5	fifth generation ECMWF atmospheric reanalysis of the global climate
ESS	Energy Storage System
ETSAP	Energy Technology Systems Analysis Programme
EV	Electric Vehicle
FACTS	Flexible Alternating Current Transmission System
GCMs	Global Climate Models
GEOS	Goddard Earth Observing System
GHGs	Greenhouse Gases
GWh	Giga watt-hour
HadGEM2-ES	Hadley Centre Global Environment Model version 2

IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPP	Independent Power Producer
IRENA	International Renewable Energy Agency
KEKELI	Power Company
Kw	Kilo Watt
kWh	Kilo watt-hour
LCOE	Levelized Cost of Energy
LT	Long term
m	meter
m ²	meter square
MERRA-2	Second version datasets of Modern-Era Retrospective analysis for Research and Applications
mm	millimeter
MME	Ministère des Mines et de l'Energie
Mono-Si	Monocrystalline
MPE	Mean Percentage Error
MPI-ES-MR	Max-Planck-Institute Earth System Model
MPPT	Maximum Power Point Tracking
MVIRI	Meteosat Visible Infra-Red Imager
MW	Mega watt
NASA	National Aeronautics and Space Administration
NorESM-1	Norwegian Climate Center's Earth System Model
Poly-Si	Polycrystalline
PV	Photovoltaic
PV _{ct}	Photovoltaic cell temperature
PVGP	Photovoltaic Generation Potential
RCP	Representative Concentration Pathways
RE	Renewable Energy
RegCM4	Regional Climate Model version 4
RMSE	Root Mean Square Error
RT	Republique Togolaise
SARRAH-2	Surface Solar Radiation Data Set-Heliosat Edition 2
SCADA	Supervisory Control and Data Acquisition
SDGs	Sustainable Development Goals
SEVIRI	Spinning Enhanced Visible and InfraRed Imager
SG	Smart Grid
SHS	Solar Homes Systems
SOLEGIE	Power Company
SOLEVA	Power Company
SSA	<i>Sub-Saharan Africa</i>
STC	Standard Test Conditions

TMMs	Typical Meteorological Months
TMY	Typical Meteorological Year
UNSD	United Nations Statistics Division
WASCAL	West African Science Service Centre on Climate Change and Adapted Land Use
WB	World Bank
Wp	Watt peak

Chapter 1 Introduction

1.1 Background

Energy access is essential for economic growth, human development, and environmental sustainability (IEA, 2017). Yet, worldwide electricity access rated 91% in 2020 and 733 million of the global population lacked access to electricity with the majority of them (77%) in Sub-Saharan Africa, (SSA)(IEA, IRENA, UNSD, WB, 2022). Globally, rural energy access is 83% compared to the urban rate of 97% in 2020. Given the progress noticed during 2018-2020, 8% of the World population would still need access to electricity of which 89% would be in SSA by 2030. In order to tackle the electricity deficit, seventeen (17) Sustainable Development Goals (SDGs) were adopted by the United Nations in 2015. Target 7 of the SDGs focuses on ensuring affordable, reliable, and sustainable energy for all (SDGs7) by 2030. Thus far, this target remains a challenge in many countries. In SSA One-third of the countries lack energy access and face more than one weekly disruption in energy supply. The disruption lasts over four minutes according to Custodian agencies (2019). Across the Globe, electricity depends heavily on traditional sources, such as oil, coal, gas, and nuclear. A comparative primary energy consumption done in 2016 gave a share of 35.96%, 28.61%, 22.89%, and 5.73% in 2005 and 32.49%, 29.84%, 23.85%, and 4.44% in 2015, respectively for the aforementioned sources. At the same time, the energy consumption resulting from renewable energy (i.e., hydro, wind, solar, and other) represented only 7.82% in 2005 and 9.57% in 2015 2015 (ADB, 2019). Decades ago, the climate has been changing as a result of global warming that is degrading the environment. Since the industrial revolution, the atmospheric GHGs have increased due majorly to anthropogenic activities. Among those activities, energy generation from fossil fuels takes the lead in GHGs emissions. Accordingly, fossil-fuels based electricity generation has significantly contributed to the enhancement of atmospheric GHGs concentrations by up to about 70% globally (Ahmed & Zahedi, 2011). Although fossil fuels constitute the back stone of global economic growth and human well-being, they are neither clean nor renewable. To the adverse impacts (increasing in temperature, changes in rainfall patterns, extreme weather events — drought, flooding, sea level rise, etc) of climate change and climate variability, Africa is the most vulnerable continent according to the International Panel on Climate Change (IPCC) (A. Githeko, M. Medany, B. Osman-Elasha, 2007).

The African continent has the largest electricity access deficit that hinders the economic and human development (IEA,2017). In 2017, only 51% of the African population had access to electricity and the per capita energy consumption was around 175 kilowatts-hour(kWh) although the global average was 2855kWh per capita (ADB, 2019). The energy access in the continent is not uniform. The electricity access rates in North and South Africa are the highest while in SSA it is the lowest. SSA has the largest population density in the world without access to energy (IEA, 2017). As a result, 57% of the population in SSA (representing 590 million) lacked access to electricity in 2017 (IEA, 2017). Hence, 80% of the above-mentioned population dwells in rural areas, where the electrification rate is around 25% compared with 71% in urban areas according to IEA in 2017. Also, more than 50% of SSA's population in 2017 relied on the traditional use of solid biomass for cooking and heating with related consequences (Avila et al., 2017; IEA, 2017). Unlike developed and other emerging nations, SSA is characterized by deficit access to electricity, limited consumption, high cost of electricity tariffs that remain unaffordable, and unreliable with high outages, as reported by IEA (2017).

In SSA, most enterprises use generators as a coping strategy. The western part of SSA, i.e., West Africa (WA), is a group of 15 countries. A population of 370 million live in WA, out of that, 55% of it resides in rural areas in 2017. The whole region is stressed by inefficient access to electricity. Wherein, less than 50% have access to electricity, viz., over 170 million lived without electricity in 2017 according to WB. The energy access challenge is so pronounced that on average, an inhabitant consumes only 160 kWh per year; this is the lowest per capita electricity consumption in the World. Also, its Member States are characterized by their energy poverty (Workshop, 2015) and they are facing various challenges, such as energy access, energy security, climate change adverse effects, and ageing power. These issues cause inefficiencies and tremendous energy losses ranging from 15% to 40% (Bazilian et al., 2011; ECREEE, 2012). In WA, the existing electricity is unsecured and unreliable, which results in frequent power shortages. In 2017, from the WB analysis, the root causes underlying the power sector issues are (a) a limited sector planning and institutional capacity to expand the electricity sector in a coherent and cost-efficient manner; (b) a lack of total adequate transmission infrastructure inside and between countrywide electricity structures that hinders the opportunity to link far sources of electrical energy to the predominant consumption centres; and (c) limited investment in electricity distribution and rural electrification (WB, 2018b). The ongoing development with the population growth in the region subsets a burden

on the power demand. Moreover, under the changing climate scenario, the existing power grids are not resilient. They do not offer the possibility for good demand response management, nor do they integrate enough renewable energy resources ((DE, 2015; IEA ETSAP & IRENA, 2015). Togo, one of the countries in WA (Figure 1_1), is characterized by the above challenges pertaining to the power sector.

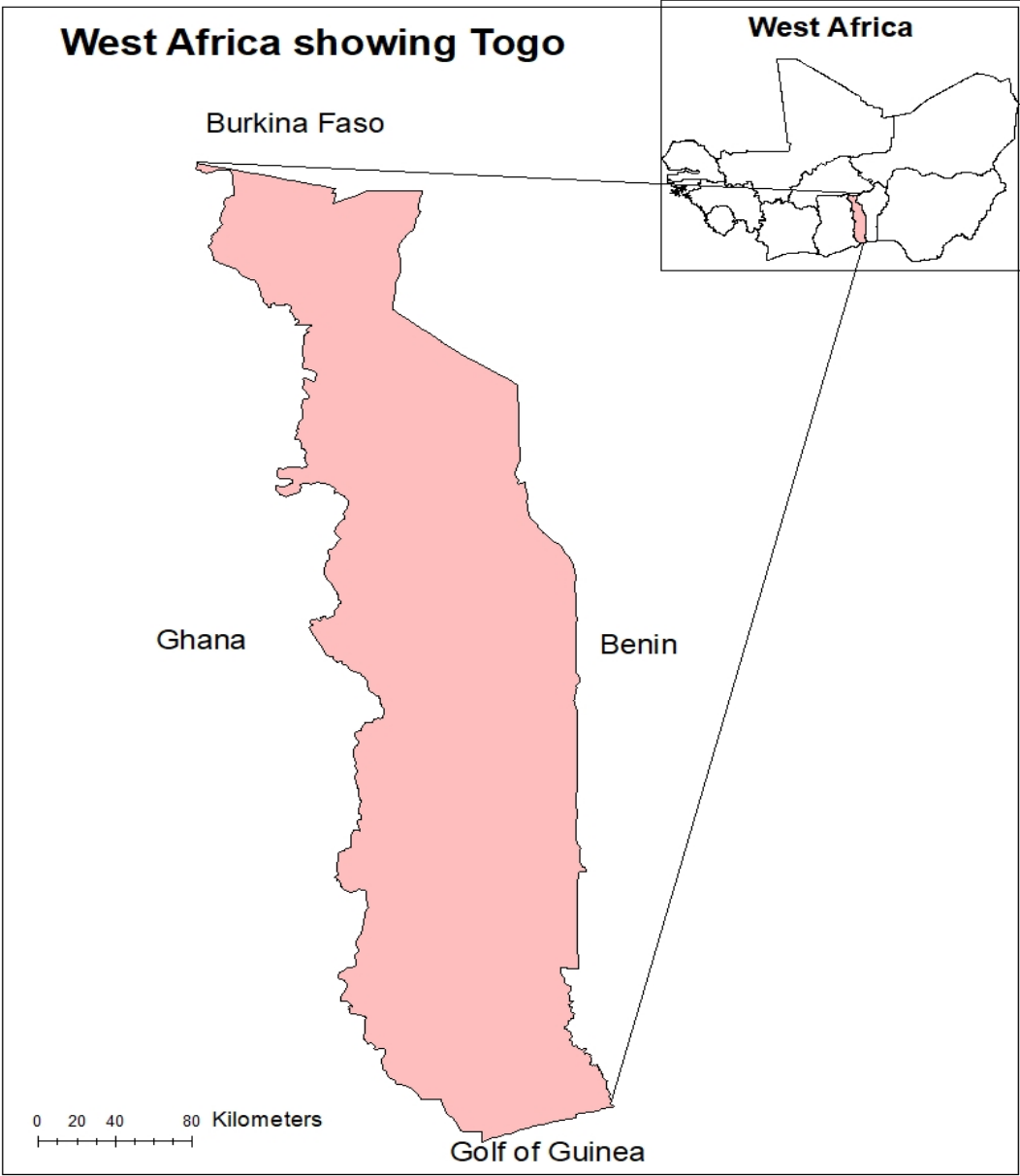


Figure 1-1: Togo, a West Africa country

The major issues of the Togolese power sector are the security of supply, reliability, and efficiency. The electricity supply depends heavily on imports from neighbouring countries. The energy

demand is increasing due to significant population growth that puts a burden on the energy sector, which is frequently impacted by supply disruption due to issues encountered in electricity generation and transmission in Nigeria and Ghana countries. Moreover, the ageing transmission and distribution infrastructures entail significant deterioration losses and reduced-service quality in the country. Besides, the sector is in an unsustainable situation attributable to 1) a systemic lack of planning capability; 2) an absence of an operational regulator with a systematic pricing mechanism; 3) an obsolete organizational and legal framework; 4) a poor utility performance; and 5) a shortage of financial resources for new investments and private sector (WB, 2018a).

With regard to the changing climate, one of the goals of most energy policies is to use and promote new energy sources that are less polluting. Robust and sustainable energy systems are the solutions for recurring power sector bottlenecks because they have the potential not only to adapt to climate change but also to mitigate the subsequent effects. Sustainable energy systems are secure, reliable, environmentally friendly, and capable of meeting the increasing energy demand (IEEE, 2008). Subsequently, integrating renewable energy onto the grid is important to balance the interconnected electricity system (Barzola et al., 2016). The WA countries' power systems have to meet the criteria of sustainability before offering the possibility to tackle the interrelated electric problems. With a sustainable energy system, the region would be able to lower GHG emissions and enhance the existing intermittent energy access, increase energy security, reliability and availability, and alleviate the burden on the ageing distribution infrastructure (Avila et al., 2017). Today, it is very important to choose which source of energy to be used and why. Factors such as cleanliness, cost, stability, efficiency, and environmental effects must be taken into account (Shahzad, 2012). Traditional sources, such as coal, oil, and natural gas (NG) are depleting and responsible for 70% of GHG emissions in the World (Ahmed & Zahedi, 2011). Consequently, it becomes crucial to think of alternative sources of energy that are less polluting. Renewable energy resources, such as solar, wind, bioenergy and hydropower are carbon-neutral fuels. Interestingly, RE is naturally replenishable and therefore infinite at a human scale. Also, RE offers the opportunity to contribute to (1) social and economic development; (2) energy access; (3) energy security; (4) climate change mitigation; and (5) reducing environmental and health impacts. In addition, they offer the possibility to improve access to modern energy services for poor people (Sathaye et al, 2011). Thailand, China, and Mexico achieved universal electricity recently based on decentralized renewable energy (DRE) systems, which are proved effective in providing

electricity access to deprived communities (Vallecha & Bhola, 2019). However, modern technology is required for its development.

Technology for upgrading and transforming the power sector is the intelligent power system known as the smart grid. This technology is a solution for interconnecting and managing a variety of energy resources (M. S. Hossain et al., 2016). The smart grid (SG) is the electrical integration onto the grid of 1) renewable energy resources, 2) energy efficiency schemes, 3) energy storage systems (ESS), and 4) reduction in carbon dioxide emissions. Hence, it would play a key role in emissions reduction in long run (Cheng, 2014; Yacout, 2015). The intelligent grid incorporates electronic power conditioning units and offers the possibility to control the production and distribution of electricity (Alvarez et al., 2014; EPRI, 2008, 2015; Naus, 2017). The SG is used to supply electricity to consumers via a two-way digital communication system (Shafiullah et al., 2013; UNECE, 2015). It offers the possibility to real-time monitor, analyse, control, and communicate within the supply chain in order to improve efficiency, reduce energy consumption and cost, and enhance the electricity supply's reliability and transparency (Brown, 2008). This arising system is developed to overcome the weaknesses of conventional electrical grids by using smart and net metering strategies. With its potential, SG controls and predicts peak demands, deals with global warming scenarios, increases the resiliency of the system, and fosters energy independence (Harrouz & Abbes, 2017). With SG technology, a sustainable energy system can be possible to bridge the gap between the supply and the increasing supply (GIZ, 2017).

Sustainable development needs access to secure and reliable clean energy because in developing economies, socioeconomic backwardness is majorly due to limited access to electricity (Vallecha & Bhola, 2019). Therefore, there is a critical need to reform the energy sector as a whole (Ahmed & Zahedi, 2011). Historically, energy production is more centralized, thus it was more vulnerable to natural disasters. The produced energy is transported over long distances to load centres through the distribution system. As a result, significant energy is lost through the lines. Additionally, the ageing energy infrastructure exacerbates the losses. Pursing the objective of meeting the present electricity demand without compromising the need of future generations, a robust power system is required to sustain all generation, transmission and distribution components (Galli et al., 2011). In the future, the major sources of energy will most likely be RE. As such, a sustainable energy system that integrates a smart grid with low-carbon energy resources is a key to the transition from

the current technology to the future ones (Bu et al., 2011; Forner et al., 2010). This could help to improve energy reliability, and energy efficiency, and limit energy losses in Sub-Saharan Africa.

1.2 Problem statement

The Togolese national electrification rate was 51.35% in 2019 according to WB. In the same year, the electricity access rate was 80% in urban areas and 10% in rural, where live about 60% of the population (DGE 2017). Togo depends heavily on biomass; this dependence is about 75.5% of daily energy needs (DGE 2017). Based on those statistics, the country remains far from achieving the objectives of universal access to electricity. Up to 2019, total power of 230 MW was installed in the country representing an equivalent of 828 GWh respectively. That installed power plant is composed of hydro plants, thermal plants and renewable plants (Table 1-1, 1-2, 1-3). Meanwhile, the national electricity demand was 1 403,17 GWh in 2017 (ARSE, 2017). To balance the gap between supply and demand, the country depends on electricity importation, about 54,07%, from neighbouring countries (Ghana, Nigeria, and Côte d'Ivoire) (ARSE, 2017). Also, the weakness of the country's fuel storage capacity makes its internal electricity production defenceless. Moreover, the Togolese power sector experiences power outages and shortages, high transmission and distribution (T&D) losses estimated at 24% and other inefficiencies in the metering system (Ntagungira, 2015; WB, 2018a). Its utility infrastructure, as a whole, is ageing whereas the electricity demand grows 8% per year on average while the yearly power production rate is estimated at 2% (Ntagungira, 2015). The share of renewable energy in the mix energetic is only 2% (DGE, 2017). In order to reduce the reliance on electricity importation, while increasing electricity access within the country, the State set up goals to achieve for the benefit of the population. The country attempts to reach a share of 24% of the energy mix and 45% of the installed capacity of renewable energy by 2030 (Energie, 2014). The government envisions attaining 100% national access to electricity by 2030 via grid-connected and off-grid power systems (Presidence togolaise, 2018). On the other hand, the dependence on electricity importation is projected to be reduced from 60% in 2016 to 40% by 2020 and 35% by 2022 (DGE, 2017).

The Togolese energy production potential is huge, but it is currently under-exploited. Nature has graciously granted renewable energy sources like solar energy, wind energy, biogas, and hydroelectricity. Concerning the latter, its underground potential was estimated over the entire country since 1984. Therefore, forty (40) sites of hydropower were identified; twenty-three (23) of them have a potential greater than 2 MW. Examples of such potentials are presented in table 1.

Table 1-1:Hydropower plants potential(GBANDEY, 2019)

Site	Installed capacity (MW)	Annual Production (GWh)	investment CAPEX, M€	LCOE (c€/kWh)	LCOE (FCFA/kWh)
Nangbeto	65.6	In operation			
Kpime	1.5	In operation			
Titira	23,80	94,20	59,00	6,31	41,40
Sarakawa	24,20	105,70	60,49	5,75	37,70
Tététou	64,00	261,80	126,10	4,75	31,14
Kpessi	15,90	69,50	70,20	10,28	67,40
Kolo-Kopé	17,10	75,00	59,60	8,03	52,70
Wawa	8,40	37,40	29,73	8,10	53,10
Seregbene	3,40	16,20	21,69	13,72	90,00
Baghan	5,80	25,50	27,82	11,19	73,40

If not only, all these sites were constructed but also operated at their full capacity, the bulk power would be 224 MW (Samah, 2016). Concerning solar potential, the average global solar irradiation is quite homogeneous with 4.4 kWh/m²/day. It has a power exceeding 700 Wc/m², especially in the dry season. In 2017, the agency in charge of rural electrification and renewable energy was created (AT2ER in French). In its planning up to 2030, micro photovoltaic power plants are projected to be built across the country in Dapaong, Kara, Blitta and Momé-Hagou, and some other projects (Table 1-2). The proposed 50MW solar micro plant in Blitta has been launched in February 2020.

Table 1-2:Solar PV plants (Source: AT2ER)

	Plants	Company	Power (MW)	Status
Utility Scale	PV Power Plant in Blitta	AMEA Power (PPA with CEET)	70	In construction
	PV Power Plant in Salimde in Sokode (Scaling Solar)	IPP (AT2ER)	30 - 40	Tender ongoing Planned
	PV Power Plant in Kapassi, Awendjelo in Kara (Scaling Solar)	IPP (AT2ER)	30 - 40	Tender ongoing Planned
	Mini-grids and off-grids	Takpakpieni	0.1	In Operation
	Koutoum	0.1	In Operation	
	Assoukoko	CEET	0.25	In Operation

Bavou	0.15	In Operation
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Table 1-3: Thermal plants (Source: ARSE)

Plants	Company	Power (MW)	Status
Thermal power station of Lomé headquarters (Sulzer)		12	In operation
Thermal power station of Lomé B (CTLB)		11.9	In operation
Thermal power station of Kara	CEET	4	In operation
Thermal power station of Sokode		1.5	In operation
Central thermique Contour Global	Contour Global (PPA with CEET)	100	In operation
Kekeli power station	Eranove Group (PPA with CEET)	65	In construction
Lomé Thermal Power Plant TAGS	CEB	65	In operation

Although the Togolese government is investing in an energy mix with an increasing share of renewable and mini-hydropower plants across the country, to our knowledge, there is no study on smart grid contribution to sustainable energy systems that could help tackle electricity issues in the country. This research tries to fill the gap.

Therefore, what are the ways to develop an energy system capable of solving the interrelated problems, i.e., i) energy access, ii) energy security and reliability, and iii) climate change mitigation in Togo

1.3 Research questions

1. How to solve the lack of meteorological datasets regarding RE studies in Togo?
2. How will a change in solar radiation, air temperature, offshore wind speed, and relative humidity caused by climate change impact the Togolese solar energy system for both short and long-term?

The sub-questions are:

- a) What is the impact of CC on meteorological variables (solar radiation, air temperature, offshore wind speed, and relative humidity)?
- b) How climate change will impact photovoltaic cell temperature?
- c) How climate change will impact photovoltaic generation potential?

3. What power grid model (PGM) is suitable for the Togolese electric power system to ensure electricity security, availability, and resilience in the short and long terms?

The sub-questions are:

- a) What is the status of the existing power network and what are its strengths and weaknesses?
- b) How to model the Togolese power system to act sustainable power system?
- c) What could be the structure and roadmap of a resilient power system (Case: Togo)?

1.4 Aim of the study

The study intends to make a contribution to the development of sustainable energy systems under a changing climate to tackle the interrelated power problems in Togo.

1.5 Main objective of the study

The main objective of this study is to search for a way leading to a suitable climate-resilient sustainable electric power system model in Togo, capable of enabling long-term energy security through: i) promotion of energy efficiency, ii) clean energy development, iii) improving energy supply quality and reliability, iv) reducing anthropogenic greenhouse gas (GHG), and v) increasing electricity access in Togo.

1.6 Specific objectives of the study

1. Develop a typical meteorological year for renewable energy studies in Togo as an alternative for data related issues.
2. Predict the potential impact of climate change on Togolese solar energy (PV cell temperature and PV generation potential) under representative concentration pathways (RCP) scenarios using Coordinated Regional Climate Downscaling Experiment-Common Regional Experiment (CORDEX-CORE) datasets.
3. Assess thoroughly and model the Togolese electric power system for the implementation of Smart Grid (SG) in Togo.

1.7 Research hypotheses

1. Typical meteorological year datasets are an alternative solution to the lack of meteorological data for renewable energy studies in Togo

2. The changes in weather parameters such as local temperature, humidity, wind speed, and relative humidity under climate change could enhance the intermittent nature of solar energy in the short and mid-century and its corresponding PV generation potential.
3. A suitable climate-resilient sustainable power system for Togo can be achieved through the transformation of the existing power system and the implementation of smart grid technology that enables RE, EE, energy storage systems to tackle power-related problems in Togo.

1.8 Significance of the study

The results of this study will redound to the benefit of society thinking about that secure and reliable electricity performs a significant role in economic and human well-being. The increasing electricity demand justifies the need to work on the power sector for its improvement. Thus, Researchers and energy planners struggling with a lack of data and quality issues could utilize typical meteorological year datasets developed as an alternative solution. In addition, based on light shed on the impact of climate change on solar energy under Togolese weather conditions policy-makers, investors, and energy planners could factor in this impact in the activities (feasibility studies, frequency of maintenance and monitoring, planning for alternative solutions, and responding to sudden changes in power stability and reliability) related to decentralized solar energy systems(DSES) to boost their performance. More, power operators that utilize the outcomes of this study will enhance the security, reliability and resilience of the power system.. Moreover, the analysis of the electric power system because of of smart grid realization is a necessary step toward the transformation of the systems to play an incredible role in resolving the moder-day interrelated power problems and smart transformation of the existing power system could result in a robust system. The Simscape modelling of the Togolese power system is another contribution that could intervene in the development of the existing power systems-related roadmap, a key element for sustainable transformation planning, needed by utility companies and policymakers planning. For all electrical sector actors, this study will show the evidence of the need for sustainable energy systems implementation to meet the electricity demand of the population in the short and long term.

1.9 Organizational structure of the thesis

The structure of this thesis entails four major Chapters. The first Chapter covers the general introduction that presents research rationale, goal and specific objectives. The, second Chapter explicitly deals with a development of typical meteorological year for massive renewable energy deployment in Togo. Under the second Chapter, I discussed the need of accessing the quality data and the importance of typical meteorological year datasets and the procedure of generating them. The third Chapter takes a focused look at the impact of climate change on photovoltaic technology and its generation potential over Togo in near future and mid-century. I discuss the magnitude of the impact on three type of solar cell (monocrystalline, polycrystalline and amorphous) and draw conclusions regarding the results on the importance of taking into consideration the effect of changing climate in designing and monitoring of decentralized solar systems. In the fourth Chapter, I assess and model the Togolese power network based on Simscape-MATLAB/Simulink. This has been done as prerequisite and an emphasis has been put on the need of transforming the present power systems for a better supply. Lastly, the final section is concerned with the conclusions and recommendations and future research needs.

Chapter 2 Development of typical meteorological year for massive renewable energy deployment in Togo.

2.1 Partial Abstract - 1

Renewable energy (RE) penetration assessment and the development of typical meteorological year (TMY) for five cities are considered collectively in this study. Thus, an integrated method is utilized encompassing RE integration status assessment and the Sandia method to generate the typical meteorological months of TMY. TMY and long-term data (LT) are then compared as well as a PV system of 3kWc output using TMY and LT with help of statistical errors calculation. Until 2020 solely 11.27% out of 360.02 MW capacity in electric power demand was RE (hydro and solar). LT and TMY are close for all the towns with a better closeness for Sokode. The latter predicts PV system performance within 2% of the LT in all the sites. More investment has to be put in RE sector because of its potential: 5.27 kWh/m²/day of mean solar radiation, 1,238.21 mm of average annual precipitation and 7m/s of mean wind speed at 50m above the ground.

2.2 Partial Introduction - 1

Renewable energy (RE) programs have been introduced by most countries worldwide into their energy policies as an alternative solution for defending the environment, a way to increase access to electricity, and a mechanism for poverty reduction through economic development. Over the course of the years, most of the countries have increased their respective RE portfolios. Accordingly, Togo has introduced RE into its energy generation in 2015 because the country has potential resources such as solar, micro-hydro, and wind (MME, 2015). Since 2017, an increasing solar energy system has been integrated into the energy mix through the installation of various mini-solar plants. The purpose was to increase electricity access within the country (AT2ER, 2018). Though RE quota augments, finding quality and accurate hourly/daily meteorological parameters is an issue. This is mostly due to the lack of meteorological stations and/or appropriate equipment for such measurements. Nevertheless, determining good sites necessitates accurate meteorological data assessment before executing any renewable energy related projects (S. O. Oyedepo et al., 2021). How to remedy the frequent problem of weather information in the context of Togo?

Typical meteorological year (TMY) records are utilized to nicely simulate the local weather of a particular location and facilitate the overall performance of energy systems dependent on weather

conditions. The accuracy of RE research is extended with the help that method (Fan et al., 2020; Givoni, 1998; Herrera et al., 2017). Therefore, the meteorological variables (solar radiation, air temperature, relative humidity, and wind speed) are quintessential for the study of RE systems and the simulation of buildings heating and cooling together. This understanding is equally essential for the evaluation of the performance of solar thermal and photovoltaic systems (Bilbao et al., 2004; Yang & Lam, 2007). Since variation in weather conditions is real with time due to atmospheric conditions and changing climate (Ohunakin et al., 2014), generating a location-related weather database that can portray over a year the long-term average data could make a great contribution (Bulut, 2010; Pusat et al., 2015), therein describing the local climate and giving a higher overview of renewable energy resources. The TMY data possibly simplifies with meteorological information the work to be performed in energy research such as energy systems comparison and sites selection (Patton, 2013). As such, energy experts will use them as diagnosed in (Sepúlveda et al., 2014).

Several methods have been examined for the TMY's development for a quite a number areas throughout the globe (Georgiou, 2013; Sawaqed et al., 2005). These strategies are distinctive from the statistical approach used to generate the typical meteorological months that form the TMY. The procedure varied from one method to another and so were the weather parameters selected and their accuracy (Argiriou et al., 1999; Georgiou, 2013). In 2013, Georgiou et al. reported the Gazela-Mathioulakis Crow method, the Miquel-Bilbao method, the Festa-Ratto method, the Danish method and the Sandia method as the most recent. The performance was found to be similar in the majority of these methods according to a comparative study conducted by (Argiriou et al., 1999; Ebrahimpour & Maerefat, 2010; Janjai & Deeyai, 2009; Skeiker, 2007). Furthermore, out of all the above TMY performing methods, Sandia was found to be the simplest but remained the most extensively used method (Janjai & Deeyai, 2009; Sun et al., 2017; Yang et al., 2008). The Sandia technique had been formulated by Hall et al. (1978) in Sandia Laboratories, U.S, as indicated by (Sawaqed et al., 2005). Regarding the weighting indices associated to weather parameters of the Sandia method, Georgiou et al. (2013), stated that in latest reviews, the solar irradiation related weighting indice used to be the highest. This fact was also reported by (E. Ouedraogo, O. Coulibaly, 2012) and (Ohunakin et al., 2018). These latter researches have been performed in West Africa. For all the reasons mentioned earlier, the Sandia empirical approach

was selected for the present study with the weighting index of solar radiation being the highest followed by the weighting index of the mean temperature.

Several researchers developed quite a number of TMY datasets for both constructions and renewable energy systems research in many cities or countries like Ankara (Turkey), Belgium, Burkina Faso, Canada, China, Damascus (Syria), Greece, Italy, Japan, Nicosia (Cyprus), Nigeria, Madagascar, Saudi Arabia, South Korea, Spain (Jee et al., 2012; Kambezidis et al., 2020). No existing study attempted to develop TMY data in Togo so far to our knowledge. This work was carried out to fill in the hole with the aid of making use of thirty 30 years of data, from 1991 to 2020, to approximate a representation of related local weather patterns. Hence, the typical meteorological year (TMY) performed in this study is composed of twelve typical meteorological months (TMMs). The latter TMMs were chosen to form a set of months in the form of a year's weather database. Each month in the TMY was selected using statistical criteria from any specific year, from 1991 to 2020, that best describes the optimal conditions of the location (Lam et al., 1996; Menicucci & Fernandez, 1988; Sawaqed et al., 2005; S. Wilcox & Marion, 2008). For instance, January 1994 may be chosen as the base month, February of 1998 as the second month, and so on.

The predominant objective of this study is to develop a TMY database on an hourly/daily scale for renewable energy research for four regional towns and the capital city, Lomé, using the second version datasets of Modern-Era Retrospective analysis for Research and Applications (MERRA-2). The study offers an evaluation of renewable energy integration in the socio-economic surroundings and a way of fixing the issues of lack of weather data at an hourly/daily scale in Togo.

2.3 Integration of Renewable Energy Systems in Togolese Socio-Economic environment

2.3.1 Evaluation of Renewable Energy Technologies

Togo is a coastal country situated in the Sudano-Guinean climatic zone, whereby the weather conditions offer good renewable energy resources for the country. These resources are hydropower, solar energy, wind energy, etc. (Samah, 2016). About 40 hydropower sites were identified across the country. Among these sites, 57.5% have a potential to generate 2MW to 50MW. The country receives an average annual precipitation between 1047.85 mm to 1428.57mm under the new TMY and 1111.56mm to 1415.12mm under the LT conditions. Also, the country

has an excellent solar radiation potential throughout the year. The global daily solar radiation varies from 4.97 kWh/m²/day in the South to 5.56 kWh/m²/day in the North, with an average of 5.27 kWh/m²/day under TMY compared to 4.4 kWh/m²/day found in the existing literature. Hence, Togo has an average insolation exceeding 700 Wp/m², especially in the dry season. Concerning wind energy resource, the potential is suitable for energy production, especially near the coastal areas. This study discovered that the Togolese wind energy potential is estimated, on average at 50m above the ground, to be above 4m/s. More specifically, this average wind speed is above 7m/s in the Northern part of the country.

2.3.2 Access to Electricity and Rate of Electrification

Togo is a developing and low-income country characterized by deprived access to electricity as most Sub-Saharan African and West Africa countries. The existing access is such that it is nonuniform across the country. The rates of electrification per region in 2019 are as follows: 96.70%, 65.52%, 23.84%, 31.61%, 33.91%, and 20.09%, respectively, for Lomé, Maritime region, Plateaux region, Central region, Kara region, and Savana Region (ARSE, 2020a). The urban areas are more electrified than the rural areas, with the capital city Lomé being the most electrified through the years. Even within the towns, the access is not consistent. Up to 2020, the electricity access is still around 50% at the national level, leaving about 4 million inhabitants with no access to electricity. Figure.2-1 portrays the evolution of the electricity access rate (Presidence togolaise, 2018; SIE, 2019).

2.3.3 Evolution of Electricity Demand

The national electricity demand is supplied through various sources like thermal, hydropower, solar plants, and importation from neighbouring countries, as presented in figure 2.2 (ARSE, 2021). The demand varied from 930.6 GWh, 1272.952GWh, 1358.50GWh, 1403.17GWh, 1451.78GWh, 1557.3GWh and 1638.41GWh, respectively, in 2010 and 2015 to 2020 as it can be seen from figure 2. Over the years, the country has been mostly dependent on importation. In 2020, the total power produced was 360.02MW, and it could cover half of the national needs with the corresponding electrification rate of 53%. A close analysis of the national demand allows us to admit that the share of RE is meagre. According to the utility companies (CEB and CEET), the demand would evolve from 1638,41GWh, 1706.40GWh, 2089.43GWh, 2182.68GWh, 2200.08GWh, and 2353.82GWh, in 2020, 2021, 2022, 2023, 2024 and 2025 in that order.

2.3.4 Renewable Energy Quotas

From the 1557.30 GWh generated in 2019, only 39.56MW (viz., 11.65%) was renewable, where 5.46MW (1.61%) accounted for solar energy. The quota of electricity from renewable used to be 37.59MW (11.83%) in 2018. In this latter year, 3.49MW (1.1%) was met through solar energy. Regarding the contribution of RE in the countrywide energy mix, the shares of hydro and solar have been 6.63% and 0.64%, respectively, in 2019, as indicated in Table 2-1 (ARSE, 2019). Thus, taking the year 2019 as a reference, the country would have to install a minimum additional capacity of 339.56MW before achieving 100% access to electricity under business as usual scenario. However, the reality is different. The country would have to invest more in electricity production in order to meet the growing electricity need closely dependent on growing economic development and improved human well-being.

2.3.5 Current and Future Renewable Energy Integration onto the Togolese Grid

The adoption of solar energy as a daily electricity source is growing in the country and contributing to the electricity access rate. Throughout the country individuals use solar panels to charge their mobile phones, light, and pump water. To foster the promotion and widespread use of solar energy, the Togolese authority has created in 2016 an agency in charge of rural electrification and renewable energy, named AT2ER. The following falls in that line. A rural electrification program, CIZO, was launched in the following year. In 2018, the renewable energy law has been voted to strengthen the promotion electricity production based on renewable energy (RT, 2018). Under the CIZO program, two companies (BBOXX and SOLEVA) were granted licenses to operate in the sector of solar homes systems (SHS) (RT, 2018)(World Bank, 2018). In the latter year, the government elaborated an electrification strategy (ES) targeting three technologies chosen to boost the access to electricity. ES aimed at achieving 100% electricity coverage by 2030 through grid-connected systems, mini-grids. and SHS (Presidence togolaise, 2018). The mini-grid can be described as a decentralized energy system (DES). The DES could be connected to the countrywide grid in the future if necessary. The SHSs are technologies suitable to supply an entire household or a small commercial enterprise that are far from the national grid. In addition, the SHSs are easily deployable and/or scalable up according to the needs of individual households. Because of features , three categories of SHSs are sold and they are 1) 1st category composed of Basic solar panel, battery, and 3 bulbs (Basic system), 2) 2nd category composed of solar panel, battery, 4 bulbs, 1 chargeable torch, and 1 radio (Plus system), and 3) 3rd category composed of

solar panel, battery, 4 bulbs, 1 chargeable torch, 1 radio, and 1 TV 24’’ (Premium system). The third company granted a license in 2020 is, SOLEGIE. At the end of the latter year, 42924 SHSs, 2387 SHSs and 4130 SHSs were distributed and installed respectively by BBOXX,SOLEVA and SOLERGIE(ARSE, 2020a). Table 2-2 presents the capacity installed according to the type of system.

RE sub-sector promotion is being ameliorated. The RE law encourages clean electricity production both in public and private sectors, but it remains the decree of its application. More, RE regulation’s mechanisms have been developed. Power plant and production infrastructure projects can benefit from a tax reduction. In addition, the Togolese off-grid solar market has been assessed; opportunities and barriers have been identified.

Moreover, the electrification strategy indicates:

1. The vision of the Government for universal electricity access,
2. The state of the art of the electricity sector,
3. A new strategy to achieve 100% electrification, and
4. The national electrification roadmap is developed.

Under that ES, projection scenario has been made considering grid extension option, mini-grids, and solar homes systems technologies and their corresponding investments to attain sustainable energy for all goals have also been estimated. Afterward, a number of power plants are planned, such as AMEA solar power of 50MW, scaling solar power plant in Sokode of 30-40MW, scaling solar plant in Kara of 30-40MW, Tetetou hydropower of 50MW, and Sarakawa hydropower of 24MW. Among plants mentioned early, only AMEA has been constructed and is in operation in 2021, but the data on power produced and transmitted are now yet available to the public.

The country needs to increase its generation capacity to achieve short- and long-term economic development. This fact will, in turn, increase its electricity access rate. Solar PV is one of the most promising alternatives for these economic goals. Therefore, this study focused on assessing solar potential (irradiance and PV power yields) in Togo. In line with this, developing TMY data is worthwhile for the provision of an accurate and appropriate meteorological dataset (Skeiker, 2004). The TMY is a required computer-based building simulation tool to predict the PV performance and therefore ensures the development of efficient policies (Ohunakin et al., 2018). For instance, a better sizing of photovoltaic (PV) power plants is strictly dependent on the quality of the data.

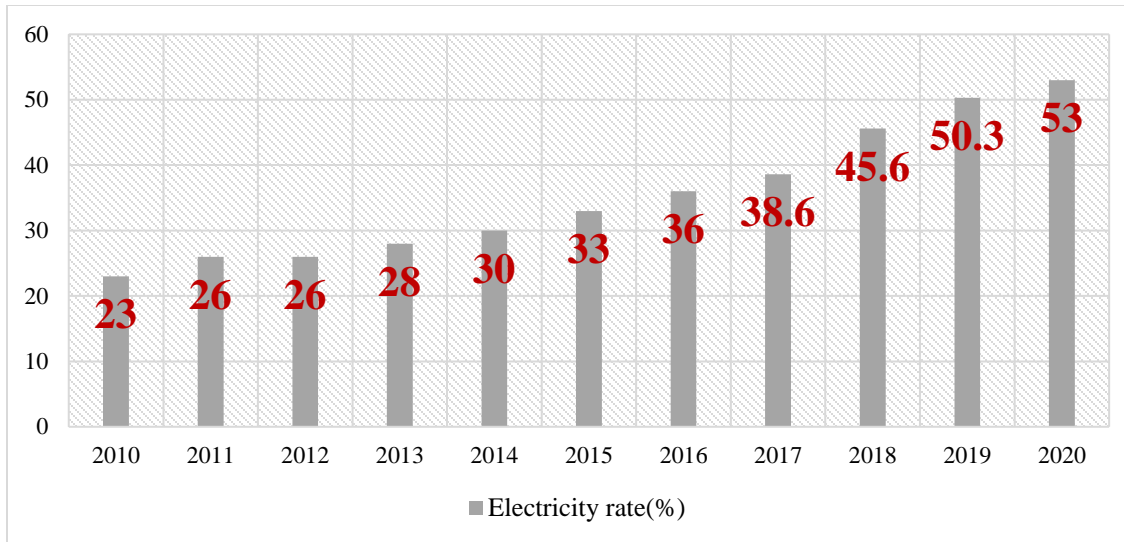


Figure 2-1:Electricity access rate

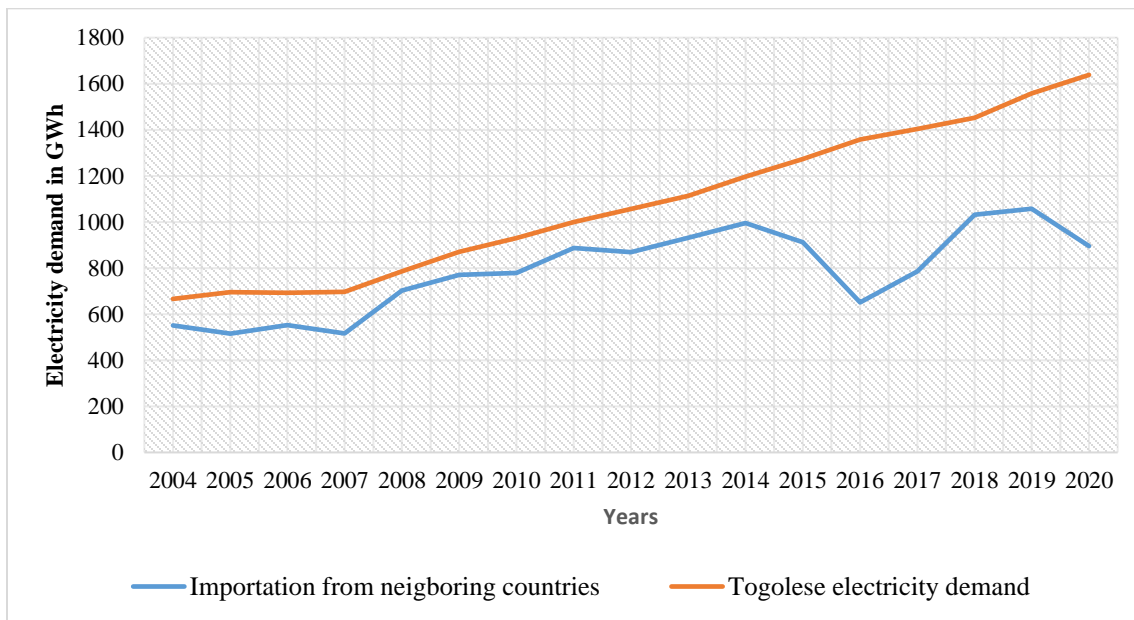


Figure 2-2:Electricity impartation share in the national electricity balance

Table 2-1 : Balance of supply sources in the national need for

Sources	Capacity balance in electricity demand				Energy mix balance			
	2019		2020		2019		2020	
	Capacity (MW)	%	Capacity (MW)	%	Demand (GWh)	%	Demand (GWh)	%
Thermal	160	47.12	160	44.44	456.83	24.25	523.58	35.16
Hydro	34.1	10.04	34.1	9.47	124.84	6.63	75.13	5.04

Solar	5.46	1.61	6.48	1.80	12.11	0.64	14.81	1
Importation	140	41.23	159.46	44.29	862.01	59.21	875.82	58.81
Balance	339.56	100	360.02	100	1455.79	100	1489.34	100

Table 2-2:Capacity installed according to technology (2020)

Companies	Type of technology	Sites	Installed capacity
CEET	Mini-grids based on solar PV	4 different sites	0.61 MW
	street light	Across the country	3.38 MW
BBOXX - EDF	Solar homes systems	Across the country	2.15 MW
SOLEVA	Solar homes systems	Across the country	0.12 MW
SOLERGIE	Solar homes systems	Across the country	0.21 MW

2.4 Development of typical meteorological years

All the processes involved in the study are presented in figure 2-3. They start from the study area selection to the review of the renewable energy penetration in the Togolese socio-economic context. As it can be seen, the methodology adopted is an integrated approach shown step by step.

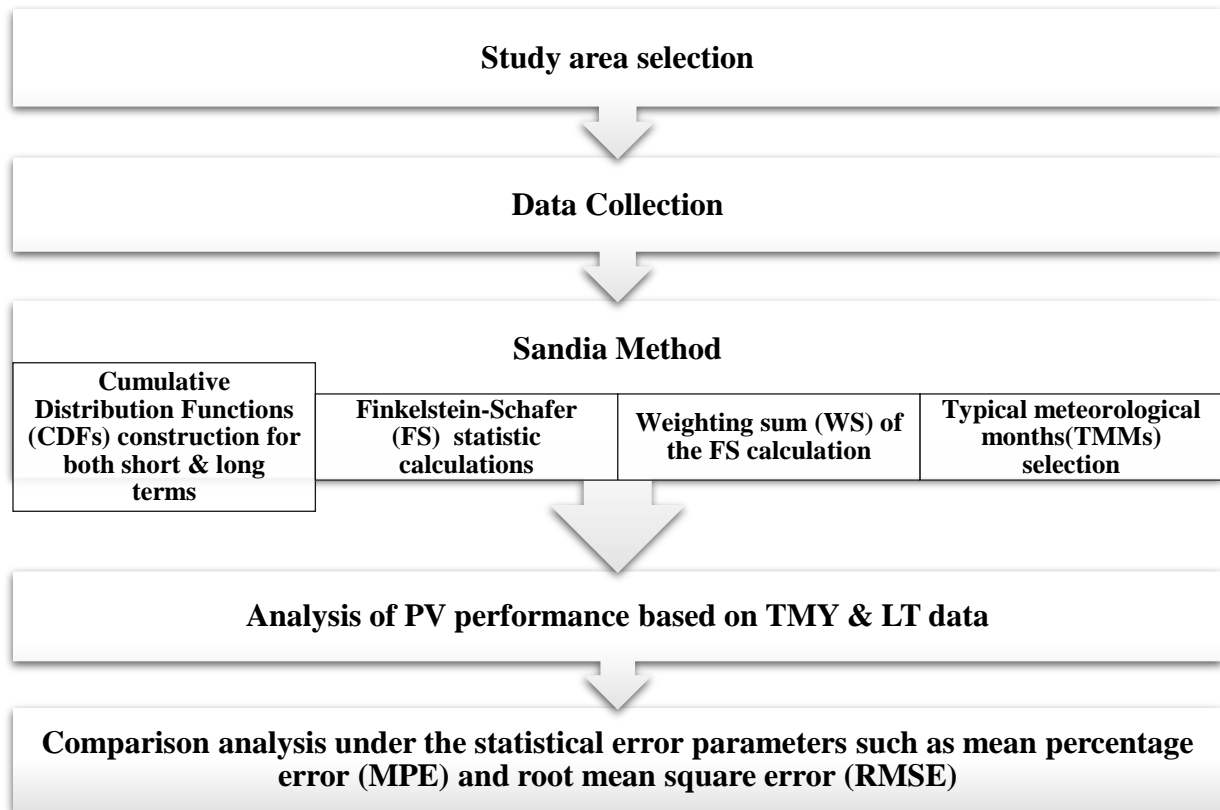


Figure 2-3:Methodology flowchart

2.4.1 Area of Study and Data

Five different geographical areas/towns were considered in this study. The five selected towns, located in the five administrative regions of Togo, were: 1) Atakpame, 2) Dapaong, 3) Kara, 4) Lome, and 5) Sokode (Figure 2-4). Lomé is the capital city of the country and the four other towns are regional capitals. Table 2-3 presents the selected towns with their respective geographic coordinates.

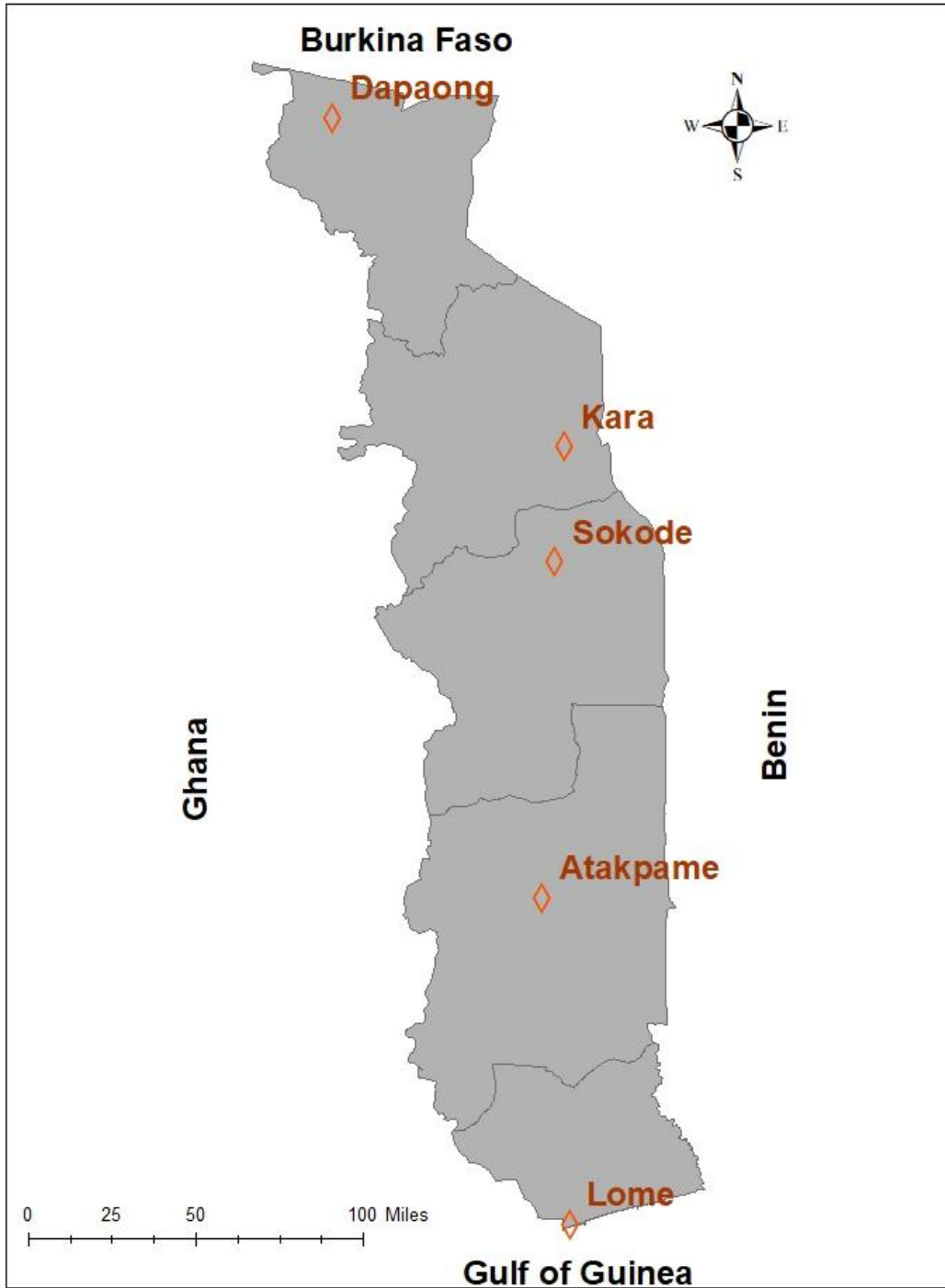


Figure 2-4: Selected Towns

2.4.2 Data collection

A set of 30 years of daily weather data from 1991 to 2020 have been considered in this study as per town. These data have been derived from MERRA 2 datasets (NASA, 2020). MERRA-2 is produced based on the version 5.12.4 of the Goddard Earth Observing System (GEOS). This system has an approximate resolution of $0.5^\circ \times 0.5^\circ$ (Gelaro et al., 2017). The related missing data had been filled based on linear interpolation using Python. The weather parameters, considered for each location in the present study, consisted of the global solar radiation, mean temperature, maximum temperature, minimum temperature, precipitation, relative humidity, and maximum wind speed. Under the Togolese climate, two weather parameters appeared to be paramount when studying solar energy systems – solar radiation and mean temperature. They were given more importance because of their weighting factors. Thereafter, global solar radiation was given the highest weighting factor as in (Sun et al., 2017). The weighting factors considered in this study are presented in Table 2-4.

Table 2-3: Selected locations

Towns	Regions	Latitude(deg)	Longitude(deg)	Data range
Atakpame	Plateaux	7.540	1.107	1991-2020
Dapaong	Savanes	10.901	0.206	1991-2020
Lome (capital city)	Maritime	6.133	1.228	1991-2020
Kara	Kara	9.484	1.206	1991-2020
Sokode	Centrale	8.986	1.162	1991-2020

Table 2-4: Weighting factors

Parameters	Weighting factor (WF)
1. Global solar radiation	5/12
2. Mean Temperature	2/12
3. Max Temperature	1/12
4. Min Temperature	1/12
5. Precipitation	1/12
6. Relative humidity	1/12
7. Maximum wind speed	1/12

2.4.3 Sandia's method

The Sandia's approach consists of the selection of individual months from different years in accordance with the period related to the study and the study area. This process involves a number of steps. In other terms, all the Januarys of the 30 selected years were analysed and the most typical was selected as the TMY's January. This procedure was carried for all the remaining 11 months of the period. The concatenation of these typical 12 months formed the complete TMY. In case the months selected belonged to different years, the discontinuities at the interfaces of those months were smoothed out on each side by 6 hours. The summary of the steps involved in the process of typical months selection are presented as follows:

Step 1: Cumulative Distribution Functions (CDFs) construction

The CDF is constructed for the long-term and the short-term daily mean values for each weather parameter chosen for the study utilizing the Eq. (2-1) (Sawaqed et al., 2005). The short-term daily mean values signify the daily mean values of a given month in a given year, whilst the long-term daily mean values stand for the average over the years for each daily mean value in a given month. In a given month of k days, the number of a given weather parameter's values is k . This parameter may assume any given daily values if the probability is h/k . The letter h represents the ranking index.

$$CDF_h = \frac{1}{k}h, h = 1, 2, \dots, k \quad (2-1)$$

Step 2: Fintnkelstein-Schafer (FS) statistic calculation

FS statistics is calculated in step 2 through the Eq. (2-2). It consists of evaluating the short-term and the long-term CDFs for each weather parameter. More details regarding the FS statistic calculations can be seen in (Fintnkelstein, 1971).

$$FS_x = \frac{1}{n} \sum_{i=1}^n |CDF_{y,m}(x_i) - CDF_m(x_i)| \quad (2-2)$$

Where, $FS_x(y, m)$ is the $FS(y, m)$ statistics for each meteorological parameter x with y and m representing the year the month, respectively. $CDF_{y,m}$ and CDF_m are respectively the short-term and the long-term cumulative distribution functions of the meteorological parameter x for the month m ; and n represents for the number of the daily value (*i.e.*, for January $n = 31$).

Step 3: Weighting sum (WS) of the FS computation.

The weather parameters of interest in the study are not equally important as it can be seen in Table 4. The weighting sum (WS) of the FS statistics was then computed for each month of the 30 years period by utilizing Eq. (2-3). Thus, WS is an aggregation of FS statistics of the seven meteorological parameters multiplied by their corresponding weighting factor.

$$WS(y, m) = \frac{1}{M} \sum_{x=1}^M W F_x \cdot F S_x(y, m) \quad (2-3)$$

Where, $WS(y, m)$ is the weighted sum of the FS for the month m in the year y . $W F_x$ represents the weighting factor of the x^{th} weather parameter; and M is the number of these parameters.

Step 4: Typical meteorological months (TMMs) choice

Finally, twelve typical months from January to December were selected on the basis of their closeness to the long-term's months. The condition of closeness is obtained with a smallest WS. Therefore, the WSs were ranked and the months with smallest WS were selected as TMMs to form the TMY database.

2.4.4 Analysis of PV performance based on TMY & LT data

It is a time-honoured reality that solar energy is highly intermittent, both in time and space (Renné, 2016). Consequently, this variability needs, not only, to be precisely estimated, but also, to be mitigated with effective energy storage for a massive grid penetration to be seen. Towards this end, the above-generated TMY was subjected to a validation process. Hence, the performance of a grid-connected photovoltaic (PV) system was simulated using the TMY and the long-term daily mean data (LT). The two most important meteorological parameters considered for the simulation were global solar radiation and mean ambient temperature. For simulation purpose, a system of 3 kW PV capacity and a 3.2 kW string inverter were chosen. The latter was 95% efficient as reported in (Ohunakin et al., 2018). The solar PV module characteristics are presented in Table 2-5. The monthly energy output ($E_{ac, m}$) was calculated through Eq. (2-4).

$$E_{ac, m} = N \cdot \frac{HT}{1 \frac{kWh}{m^2}} \cdot f_d \cdot P_{rated} \quad (2-4)$$

Where, N represents the number of days in a month, HT is the daily average global solar radiation in kWh/m^2 , P_{rated} is the rated capacity of the PV array in kW, and f_d is the PV derating factor in %; and F_d is hosts two factors – temperature-related and non-temperature related.

Table 2-5: Technical specification of MaxPower CS6X-320P

Parameter	
Cell Type	Poly-Crystalline, 6inch
Nominal Maximum Power	320wp
Optimum Operating Voltage	36.8v
Optimum Operating Current	8.69a
Open Circuit Voltage	45.3v
Short Circuit Current	9.26a
Module Efficiency	16.68%
Operating Temperature	-40~+85°C
Temperature Coefficient (Pmax)	-0.41%/°C
Temperature Coefficient (Voc)	-0.31%/°C
Temperature Coefficient (Isc)	0.053%/°C
Nominal Operating Cell Temperature	45±2°C
Dimension	1954x982x40mm

Moreover, the derating factor ($f_{nontemp}$) considers the combination of the module's nameplate DC rating, PV system's age, the inverter's efficiency mismatch, the soiling, and the shading. Moreover, an assumption of 77% was made for the non-temperature derating factor. The former derating factor (f_{Temp}) results from the difference between the *STC* reference temperature (25°C) and cells' temperature, *STC* being the Standard Test Conditions. Consequently, the f_{Temp} is computed by means of Eq. (2-5).

$$f_{temp} = 1 + \left[\left(\frac{\varepsilon}{100} \right) \cdot (T_c - T_{c,STC}) \right] \quad (2-5)$$

Where, T_c is the PV cell's temperature [°C] and ε module power coefficient [%/°C]; and $T_{c,STC}$ is the PV cell's temperature under 25°C.

It is worth pointing out that the aforementioned T_c was estimated from (Duffie & Beckman, 1982). As a result, T_c can be estimated through Eq. (2-6).

$$T_c = T_a + \left[\left(\frac{9.5}{5.7+3.8 \cdot V} \right) \cdot \left(\frac{T_{c,NOCT} - T_{a,NOCT}}{GT,NOCT} \right) \cdot GT \right] \quad (2-6)$$

Where, T_a is the ambient temperature [K]; V is wind speed of the location in m/s; $T_{c,NOCT}$ is the nominal operating cell's temperature [K]; $T_{a,NOCT}$ represents the ambient temperature at which the $NOCT$ is defined (20^0C); $G_{T,NOCT}$ equals 0.8 KW/m^2 (solar radiation at which the $NOCT$ is defined); and G_T is the solar irradiation in kW/m^2 .

Finally, the overall derating factor is calculated with the help of Eq. (2-7).

$$f_d = f_{nontemp} \cdot f_{temp} \quad (2-7)$$

2.4.5 Comparison analysis under the statistical error parameters such as mean percentage error (MPE) and root mean square error (RMSE)

A long-term (LT) evaluation and comparison of the PV system's output were conducted utilizing the generated TMY. The methodology applied was based on mean percentage error (MPE), mean bias error (MBE), and root mean square error (RMSE) as in (Ohunakin et al., 2018). The MPE statistics consists of measuring the average percentage bias between predicted values (TMY) and observed values (LT) by providing more insight about any over-estimation and under-estimation of the TMY. The RMSE simply portrays the standard deviation of the differences between the TMY and LT values. It clearly measures with accuracy the predictions. Additionally, the RMSE informs on the correlations of the short-term performance that result into comparisons of the term-by-term differences between the predicted and observed values. The predictions were good for smaller errors. Hence, the MPE and RMSE are expressed as in Eq. (2-8) and Eq. (2-9), in that order.

$$MPE = \frac{100\%}{n} \sum_{i=1}^n \frac{LTi - TMYi}{LTi} \quad (2-8)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (TMYi - LTi)^2}{n}} \quad (2-9)$$

Where, LTi and $TMYi$ are, respectively, the long-term and developed TMY variables.

2.5 Results and Discussions

2.5.1 Typical Meteorological Year (TMY)

The study attempted to construct the TMY for five selected Towns in Togo. In selecting the typical meteorological months, the indices with the highest weighting factors, such as global solar radiation and mean temperature, were utilized. The values of the FS statistics' WS for selected locations were calculated over 30 years and presented in Table 2-6 through Table 2-10. The

months with the lowest WS were selected for each month as the typical meteorological months (TMMs) over the study period. Furthermore, these selected months were written in bold as can be seen from the aforementioned tables. The bold months then automatically formed the Togolese TMY. It is necessary of word to factor out that, due to similar weather patterns, the researchers, investors, and lawmakers of the neighbouring countries — Benin, Ghana, and Burkina Faso — may greatly benefit from this TMY.

Table 2-6: Weighting sums of FS statistics calculated for Atakpame with the lowest values in bold

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1991	0.40	0.41	0.31	0.48	0.25	0.16	0.13	0.13	0.19	0.09	0.32	0.37
1992	0.15	0.26	0.18	0.28	0.12	0.15	0.11	0.17	0.15	0.15	0.26	0.25
1993	0.67	0.23	0.22	0.38	0.13	0.18	0.09	0.11	0.08	0.11	0.44	0.35
1994	0.17	0.29	0.22	0.41	0.15	0.10	0.17	0.17	0.16	0.10	0.22	0.14
1995	0.63	0.27	0.12	0.25	0.13	0.17	0.10	0.21	0.14	0.07	0.33	0.22
1996	0.22	0.17	0.18	0.33	0.18	0.12	0.14	0.19	0.14	0.11	0.45	0.16
1997	0.20	0.48	0.25	0.45	0.15	0.31	0.23	0.17	0.10	0.11	0.15	0.27
1998	0.36	0.59	0.24	0.48	0.17	0.16	0.15	0.17	0.18	0.12	0.22	0.39
1999	0.31	0.34	0.12	0.33	0.21	0.24	0.10	0.25	0.09	0.17	0.22	0.24
2000	0.29	0.37	0.25	0.48	0.27	0.18	0.10	0.15	0.16	0.13	0.09	0.38
2001	0.46	0.41	0.13	0.30	0.09	0.15	0.08	0.14	0.14	0.16	0.20	0.21
2002	0.56	0.33	0.18	0.38	0.15	0.19	0.12	0.12	0.14	0.12	0.29	0.39
2003	0.34	0.33	0.23	0.44	0.29	0.08	0.16	0.12	0.14	0.10	0.18	0.25
2004	0.32	0.36	0.19	0.39	0.17	0.13	0.10	0.16	0.08	0.12	0.18	0.34
2005	0.37	0.39	0.20	0.38	0.13	0.21	0.12	0.11	0.17	0.16	0.19	0.28
2006	0.14	0.34	0.14	0.26	0.24	0.16	0.13	0.27	0.07	0.12	0.30	0.43
2007	0.51	0.66	0.22	0.46	0.26	0.14	0.29	0.13	0.18	0.20	0.18	0.38
2008	0.46	0.22	0.24	0.39	0.16	0.12	0.09	0.10	0.14	0.12	0.14	0.36
2009	0.47	0.40	0.25	0.48	0.32	0.14	0.11	0.13	0.14	0.27	0.21	0.25
2010	0.15	0.37	0.21	0.30	0.14	0.17	0.21	0.13	0.13	0.15	0.10	0.26
2011	0.40	0.34	0.17	0.37	0.15	0.08	0.20	0.16	0.15	0.14	0.13	0.16

2012	0.26	0.19	0.34	0.45	0.14	0.16	0.15	0.12	0.14	0.22	0.15	0.20
2013	0.33	0.36	0.13	0.24	0.10	0.18	0.15	0.20	0.09	0.09	0.33	0.27
2014	0.24	0.39	0.18	0.39	0.13	0.22	0.13	0.15	0.09	0.08	0.24	0.33
2015	0.43	0.35	0.31	0.31	0.17	0.20	0.18	0.12	0.15	0.16	0.22	0.43
2016	0.28	0.48	0.23	0.41	0.19	0.17	0.14	0.11	0.09	0.21	0.25	0.26
2017	0.27	0.63	0.11	0.31	0.10	0.12	0.17	0.07	0.12	0.17	0.35	0.24
2018	0.41	0.36	0.10	0.24	0.19	0.21	0.18	0.21	0.16	0.10	0.20	0.35
2019	0.29	0.40	0.17	0.41	0.16	0.23	0.14	0.12	0.12	0.11	0.16	0.23
2020	0.38	0.30	0.15	0.36	0.15	0.17	0.18	0.25	0.15	0.16	0.33	0.18

Table 2-7: Weighting sums of FS statistics calculated for Dapaong with the lowest values in bold

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1991	0.09	0.45	0.17	0.27	0.23	0.14	0.11	0.09	0.13	0.16	0.33	0.69
1992	0.20	0.17	0.64	0.31	0.22	0.15	0.07	0.21	0.12	0.14	0.35	0.08
1993	0.16	0.35	0.47	0.26	0.14	0.20	0.10	0.21	0.08	0.14	0.44	0.76
1994	0.27	0.56	0.12	0.16	0.16	0.20	0.17	0.12	0.18	0.20	0.39	0.10
1995	0.13	0.45	0.24	0.18	0.15	0.10	0.16	0.19	0.16	0.08	0.24	0.34
1996	0.22	0.26	0.46	0.13	0.16	0.13	0.12	0.22	0.09	0.15	0.12	0.48
1997	0.41	0.49	0.47	0.12	0.21	0.21	0.16	0.15	0.13	0.13	0.22	0.68
1998	0.58	0.98	0.36	0.26	0.11	0.12	0.12	0.14	0.18	0.12	0.44	0.52
1999	0.30	0.44	0.38	0.16	0.11	0.11	0.14	0.22	0.12	0.18	0.31	0.11
2000	0.44	0.11	0.35	0.12	0.18	0.14	0.08	0.26	0.16	0.15	0.20	0.18
2001	0.10	0.16	0.34	0.18	0.16	0.13	0.23	0.11	0.08	0.31	0.43	0.15
2002	0.51	0.23	0.22	0.40	0.12	0.18	0.15	0.12	0.13	0.26	0.34	0.14
2003	0.36	0.50	0.35	0.19	0.35	0.13	0.15	0.12	0.11	0.09	0.30	0.10
2004	0.28	0.34	0.12	0.17	0.15	0.15	0.12	0.15	0.18	0.20	0.24	0.33
2005	0.48	0.41	0.32	0.11	0.15	0.10	0.15	0.12	0.19	0.23	0.34	0.58
2006	0.44	0.58	0.21	0.24	0.19	0.15	0.17	0.13	0.20	0.09	0.38	0.13
2007	0.15	0.86	0.50	0.11	0.21	0.23	0.20	0.11	0.21	0.51	0.17	0.77
2008	0.50	0.30	0.21	0.26	0.24	0.38	0.19	0.11	0.11	0.15	0.45	0.68

2009	0.36	0.49	0.16	0.16	0.24	0.22	0.09	0.12	0.15	0.33	0.23	0.44
2010	0.31	0.52	0.35	0.18	0.09	0.18	0.11	0.12	0.13	0.13	0.20	0.08
2011	0.49	0.49	0.26	0.17	0.09	0.12	0.16	0.13	0.14	0.15	0.21	0.08
2012	0.24	0.28	0.29	0.25	0.19	0.13	0.12	0.18	0.11	0.21	0.20	0.48
2013	0.33	0.41	0.17	0.16	0.10	0.13	0.14	0.12	0.15	0.14	0.54	0.59
2014	0.21	0.38	0.41	0.21	0.26	0.22	0.09	0.26	0.12	0.15	0.10	0.07
2015	0.27	0.47	0.36	0.37	0.13	0.10	0.15	0.09	0.16	0.11	0.32	0.06
2016	0.11	0.41	0.29	0.32	0.20	0.21	0.13	0.10	0.09	0.15	0.25	0.43
2017	0.06	0.97	0.26	0.25	0.11	0.19	0.12	0.12	0.12	0.28	0.49	0.08
2018	0.07	0.48	0.24	0.16	0.16	0.18	0.15	0.11	0.30	0.11	0.20	0.08
2019	0.25	0.96	0.33	0.20	0.11	0.20	0.21	0.19	0.12	0.12	0.19	0.08
2020	0.12	0.10	0.23	0.19	0.20	0.16	0.15	0.17	0.21	0.21	0.73	0.57

Table 2-8: Weighting sums of FS statistics calculated for Kara with the lowest values in bold

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
s												
1991	0.41	0.42	0.28	0.25	0.27	0.17	0.10	0.10	0.22	0.08	0.21	0.40
1992	0.19	0.66	0.21	0.21	0.12	0.16	0.19	0.16	0.14	0.12	0.32	0.39
1993	0.15	0.29	0.31	0.21	0.14	0.18	0.10	0.13	0.11	0.13	0.46	0.52
1994	0.26	0.30	0.15	0.17	0.20	0.14	0.13	0.13	0.17	0.17	0.32	0.10
1995	0.67	0.49	0.23	0.16	0.14	0.18	0.13	0.14	0.15	0.13	0.27	0.22
1996	0.27	0.24	0.29	0.14	0.21	0.16	0.12	0.24	0.12	0.15	0.53	0.29
1997	0.36	0.49	0.29	0.17	0.16	0.10	0.18	0.24	0.17	0.13	0.17	0.31
1998	0.52	0.75	0.33	0.29	0.11	0.17	0.17	0.15	0.21	0.16	0.26	0.40
1999	0.27	0.41	0.17	0.22	0.13	0.14	0.12	0.16	0.15	0.11	0.16	0.54
2000	0.54	0.31	0.37	0.09	0.28	0.16	0.10	0.29	0.17	0.11	0.16	0.42
2001	0.50	0.35	0.21	0.20	0.12	0.13	0.18	0.12	0.16	0.18	0.23	0.09
2002	0.54	0.37	0.18	0.25	0.13	0.16	0.16	0.10	0.11	0.22	0.26	0.44
2003	0.39	0.45	0.29	0.19	0.32	0.10	0.13	0.14	0.16	0.12	0.30	0.19
2004	0.31	0.38	0.29	0.12	0.15	0.17	0.12	0.12	0.15	0.10	0.17	0.42
2005	0.41	0.37	0.30	0.16	0.18	0.12	0.22	0.12	0.20	0.27	0.22	0.30

2006	0.23	0.38	0.11	0.24	0.25	0.18	0.17	0.16	0.14	0.14	0.35	0.53
2007	0.52	0.81	0.44	0.20	0.29	0.17	0.18	0.14	0.15	0.25	0.18	0.47
2008	0.45	0.26	0.20	0.25	0.13	0.15	0.12	0.12	0.16	0.12	0.24	0.40
2009	0.45	0.41	0.33	0.18	0.33	0.11	0.13	0.18	0.12	0.33	0.22	0.32
2010	0.21	0.39	0.26	0.17	0.28	0.13	0.16	0.12	0.16	0.15	0.20	0.39
2011	0.50	0.36	0.18	0.13	0.11	0.09	0.15	0.10	0.15	0.14	0.20	0.12
2012	0.34	0.24	0.47	0.24	0.19	0.15	0.16	0.14	0.18	0.28	0.13	0.37
2013	0.34	0.40	0.12	0.13	0.10	0.13	0.23	0.19	0.13	0.13	0.47	0.28
2014	0.46	0.43	0.26	0.22	0.16	0.19	0.14	0.21	0.13	0.12	0.15	0.38
2015	0.47	0.47	0.43	0.29	0.17	0.18	0.16	0.20	0.11	0.13	0.33	0.07
2016	0.15	0.44	0.22	0.27	0.24	0.29	0.14	0.10	0.14	0.13	0.20	0.34
2017	0.27	0.87	0.24	0.18	0.16	0.23	0.14	0.13	0.15	0.28	0.46	0.21
2018	0.05	0.50	0.15	0.19	0.15	0.19	0.20	0.19	0.23	0.15	0.20	0.07
2019	0.37	0.39	0.18	0.18	0.13	0.28	0.19	0.14	0.19	0.16	0.25	0.35
2020	0.43	0.32	0.16	0.14	0.17	0.16	0.15	0.32	0.13	0.21	0.73	0.27

Table 2-9: Weighting sums of FS statistics calculated for Lomé with the lowest values in bold

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
s												
1991	0.46	0.33	0.28	0.19	0.22	0.16	0.17	0.19	0.15	0.11	0.28	0.41
1992	0.09	0.26	0.25	0.16	0.15	0.17	0.12	0.25	0.15	0.15	0.23	0.19
1993	0.46	0.27	0.18	0.16	0.12	0.14	0.18	0.17	0.08	0.12	0.35	0.36
1994	0.28	0.30	0.23	0.22	0.21	0.20	0.16	0.29	0.14	0.13	0.24	0.12
1995	0.50	0.39	0.11	0.20	0.21	0.20	0.16	0.24	0.12	0.13	0.45	0.17
1996	0.18	0.12	0.10	0.19	0.15	0.15	0.23	0.17	0.15	0.16	0.53	0.12
1997	0.32	0.45	0.18	0.15	0.15	0.16	0.28	0.20	0.21	0.10	0.28	0.21
1998	0.46	0.53	0.19	0.20	0.17	0.13	0.17	0.28	0.19	0.16	0.20	0.21
1999	0.28	0.37	0.08	0.15	0.28	0.31	0.13	0.32	0.09	0.17	0.22	0.24
2000	0.21	0.31	0.22	0.11	0.12	0.25	0.16	0.24	0.19	0.15	0.11	0.29
2001	0.28	0.48	0.18	0.12	0.09	0.18	0.20	0.20	0.13	0.16	0.20	0.13
2002	0.46	0.32	0.15	0.19	0.14	0.23	0.18	0.18	0.16	0.09	0.21	0.32

2003	0.22	0.32	0.18	0.19	0.17	0.16	0.23	0.14	0.16	0.12	0.10	0.20
2004	0.29	0.23	0.19	0.12	0.22	0.32	0.13	0.16	0.14	0.15	0.26	0.29
2005	0.55	0.30	0.06	0.18	0.17	0.18	0.19	0.32	0.21	0.10	0.21	0.26
2006	0.18	0.29	0.11	0.20	0.22	0.13	0.17	0.32	0.16	0.16	0.32	0.37
2007	0.51	0.57	0.24	0.29	0.16	0.15	0.28	0.17	0.26	0.10	0.18	0.29
2008	0.42	0.23	0.33	0.25	0.22	0.12	0.30	0.19	0.11	0.16	0.17	0.35
2009	0.34	0.37	0.22	0.14	0.33	0.28	0.11	0.16	0.15	0.25	0.25	0.22
2010	0.14	0.39	0.15	0.12	0.18	0.18	0.27	0.15	0.13	0.10	0.12	0.20
2011	0.22	0.34	0.13	0.13	0.12	0.18	0.20	0.19	0.20	0.17	0.15	0.28
2012	0.41	0.17	0.24	0.12	0.19	0.27	0.18	0.16	0.25	0.19	0.21	0.16
2013	0.41	0.31	0.14	0.13	0.10	0.22	0.17	0.22	0.12	0.07	0.21	0.28
2014	0.14	0.24	0.18	0.13	0.14	0.24	0.19	0.17	0.10	0.10	0.31	0.32
2015	0.41	0.43	0.29	0.27	0.20	0.19	0.31	0.16	0.25	0.14	0.27	0.41
2016	0.25	0.39	0.15	0.14	0.17	0.25	0.18	0.16	0.16	0.18	0.18	0.21
2017	0.31	0.33	0.15	0.17	0.15	0.19	0.15	0.08	0.13	0.08	0.26	0.23
2018	0.34	0.44	0.08	0.32	0.19	0.12	0.16	0.22	0.16	0.11	0.11	0.15
2019	0.41	0.30	0.17	0.13	0.18	0.13	0.20	0.19	0.15	0.17	0.17	0.20
2020	0.34	0.37	0.16	0.15	0.16	0.27	0.23	0.23	0.15	0.09	0.17	0.15

Table 2-10: Weighting sums of FS statistics calculated for Sokode with the lowest values in bold

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1991	0.40	0.45	0.28	0.17	0.22	0.17	0.10	0.13	0.23	0.10	0.23	0.35
1992	0.17	0.58	0.17	0.22	0.12	0.15	0.15	0.17	0.15	0.13	0.30	0.36
1993	0.16	0.27	0.28	0.20	0.16	0.15	0.12	0.11	0.10	0.12	0.46	0.46
1994	0.23	0.28	0.18	0.18	0.17	0.12	0.15	0.11	0.15	0.13	0.28	0.13
1995	0.68	0.48	0.18	0.18	0.16	0.17	0.16	0.13	0.13	0.11	0.26	0.22
1996	0.26	0.21	0.28	0.15	0.21	0.11	0.13	0.22	0.14	0.13	0.36	0.27
1997	0.24	0.50	0.31	0.15	0.15	0.12	0.20	0.20	0.15	0.14	0.15	0.31
1998	0.48	0.69	0.34	0.27	0.13	0.17	0.15	0.13	0.19	0.16	0.25	0.44
1999	0.25	0.39	0.15	0.16	0.16	0.13	0.11	0.16	0.12	0.11	0.20	0.54

2000	0.53	0.32	0.32	0.08	0.34	0.14	0.08	0.22	0.15	0.08	0.14	0.40
2001	0.50	0.34	0.18	0.17	0.11	0.12	0.13	0.12	0.15	0.21	0.22	0.09
2002	0.60	0.38	0.18	0.20	0.17	0.15	0.16	0.13	0.10	0.20	0.27	0.43
2003	0.38	0.42	0.26	0.16	0.28	0.09	0.13	0.14	0.15	0.13	0.29	0.22
2004	0.30	0.40	0.25	0.11	0.18	0.12	0.09	0.18	0.11	0.10	0.23	0.35
2005	0.36	0.38	0.27	0.21	0.20	0.16	0.21	0.12	0.21	0.22	0.18	0.26
2006	0.19	0.36	0.12	0.28	0.26	0.16	0.19	0.19	0.11	0.12	0.32	0.51
2007	0.53	0.75	0.39	0.21	0.30	0.16	0.22	0.18	0.19	0.23	0.19	0.44
2008	0.44	0.23	0.20	0.24	0.14	0.16	0.11	0.12	0.17	0.12	0.23	0.37
2009	0.46	0.41	0.30	0.19	0.35	0.15	0.15	0.14	0.14	0.28	0.21	0.31
2010	0.22	0.39	0.23	0.17	0.25	0.15	0.18	0.12	0.15	0.16	0.21	0.46
2011	0.48	0.42	0.20	0.12	0.12	0.09	0.18	0.11	0.12	0.16	0.19	0.14
2012	0.31	0.24	0.47	0.20	0.18	0.16	0.16	0.13	0.14	0.29	0.10	0.31
2013	0.32	0.39	0.09	0.17	0.12	0.17	0.21	0.15	0.13	0.11	0.45	0.27
2014	0.39	0.45	0.21	0.19	0.18	0.18	0.12	0.24	0.16	0.11	0.17	0.35
2015	0.44	0.44	0.35	0.29	0.15	0.17	0.20	0.16	0.14	0.11	0.33	0.46
2016	0.47	0.50	0.20	0.29	0.23	0.24	0.12	0.10	0.12	0.14	0.22	0.32
2017	0.25	0.83	0.19	0.10	0.17	0.19	0.14	0.11	0.21	0.26	0.43	0.23
2018	0.06	0.43	0.12	0.20	0.11	0.19	0.16	0.20	0.22	0.13	0.24	0.05
2019	0.30	0.47	0.20	0.21	0.11	0.31	0.20	0.12	0.16	0.18	0.24	0.29
2020	0.41	0.31	0.15	0.14	0.21	0.20	0.16	0.29	0.15	0.20	0.62	0.24

In summary, the bold months were all compiled in Table 2-11, which presents the TMY generated for each of the selected towns. As it can be noticed from Table 2-11, the TMMs are evenly spread within the study’s period across the locations.

Table 2-11:Generated typical meteorological years for selected Towns

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ATAKPAME											
2006	1996	2018	2018	2001	2003	2001	2017	2006	1995	2000	1994
DAPAONG											
2017	2020	2004	2007	2011	2015	1992	1991	1993	1995	2014	2015

KARA											
2018	1996	2006	2000	2013	2011	1993	2011	2015	1991	2012	2018
LOME											
1992	1996	2005	2000	2001	2018	2009	2017	1993	2013	2003	1994
SOKODE											
2018	1996	2013	2000	2019	2011	2000	2016	2002	2000	2012	2018

The divergence of the TMY and LT was then analysed based on the performance indicators (MPE and RMSE) considering global solar radiation parameter. Table 2-12 shows analysis' results for the two main parameters. In that table, one can see the extent of the difference between the two values. The values of TMY are barely greater than the values of LT for Dapaong, Kara, Lome and Sokode (MPE<0); slightly lower than the values of LT for Atakpame (MPE>0).

In the case of Sokode, the MPE varies between -8.12% and 13.34% throughout the typical meteorological months. TMY overrated the LT in January, March, April, May, September, October, and December. This same TMY underestimated their counterpart's LT in the rest of the months, accordingly ensuing in a negative mean bias error of -0.03% inferior to 1%. With that percentage of error, it could be assumed that there is right settlement between predictions from the TMY and the corresponding long term means. As such, the developed TMY could be regarded as an appropriate weather database for the study and sizing of renewable energy, in particular solar energy systems and therefore, be useful for designers of solar energy systems and researchers.

In general, the TMY suits the LT for global solar irradiation in the selected towns as can be seen in Table 10 with the fine shape in Lomé (MPE= -0.26%, RMSE=0.24), Sokodé (MPE= -0.03%, RMSE=0.30) and Dapaong (MPE= -1.09%, RMSE=-0.32). Mean temperature follows in the case of Sokodé (MPE= 0.77%, RMSE=0.55). The MPE and RMSE for the rest of the parameters in the latter location were relative humidity (MPE= -4.8%. RMSE=6.73), precipitation (MPE= -4.96%. RMSE=29.37) and maximum wind speed (MPE= 1.32%. RMSE=0.47). The difference in the results related from the two weather parameters might be attributed to the importance of the global solar irradiation being assigned with a major weighting factor of 5/12 in comparison with the second with a factor of 2/12. It is important to point out that the rest of the parameters were ascribed with a weighting factor of only 1/12. Derived from the TMYs, the daily mean global solar irradiation (kWh/m²/day) in Atakpame, Dapaong, Kara, Lomé and Sokode is 5.11; 5.56; 5.46; 4.97; 5.26 respectively. With the close variation observed between the two kind of data for each

location, the TMYs could well characterize their climate and be used as input for the performance's study of renewable energy systems in the aforementioned towns and the surroundings.

Table 2-12: Performance indicators of the TMY and LT average of the main weather parameters

	Indicators	Atakpame	Dapaong	Kara	Lomé	Sokode
Global solar irradiation	MPE (%)	1.55	-1.09	-1.89	-0.26	-0.03
	RMSE	0.21	0.32	0.27	0.24	0.3
Mean temperature	MPE (%)	0.75	-0.91	0.76	0.67	0.77
	RMSE	0.88	1.01	0.49	0.47	0.55
Mean wind speed	MPE (%)	-5.12	-7.3	1.31	-0.95	0.54
	RMSE	0.37	0.77	0.51	0.23	0.38
PV energy system output	MPE (%)	1.55	-1.09	-1.89	0.2	-0.03
	RMSE	14.68	22.94	19.14	15.93	21.37

Figure 2-4 represents the climatological variation of global solar irradiation for the five locations using the TMY vs LT whereas Figures 2-5 and 2-6 illustrate the mean temperature and wind speed variations of TMY vs LT for the selected towns. A close variation is observed between the monthly average values of TMY versus LT for all the locations as portrayed in Figures 2-4, 2-5 and 2-6 based on the most important weather parameters (global solar irradiation, the mean temperature and mean wind speed). This could be explained by the small values of the FS statistics and the close fit of TMY and LT.

The variation of TMY vs LT of other weather variables considered for Sokode is presented in Figure 2-7. It can additionally be discovered that precipitation; relative humidity at 2m; minimal and maximum temperature at 2m, maximum; minimal and mean wind speed at 50m present almost

a same pattern in their trend under TMY vs LT. It is, therefore, resulted in a close variation between TMY and LT.

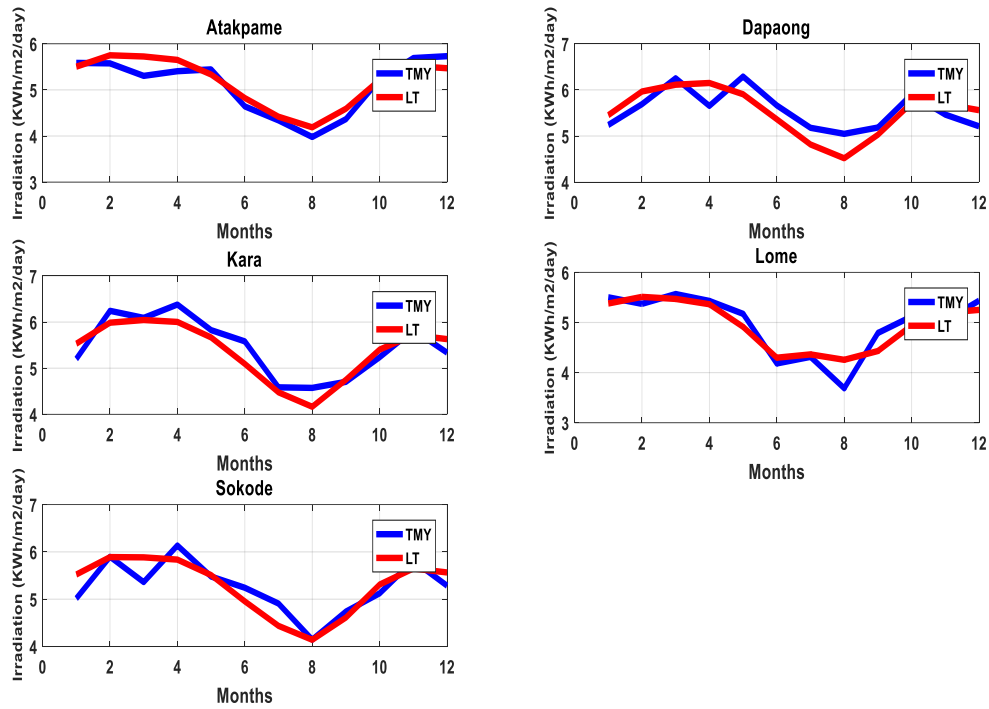


Figure 2-5: Global solar irradiation for the five locations

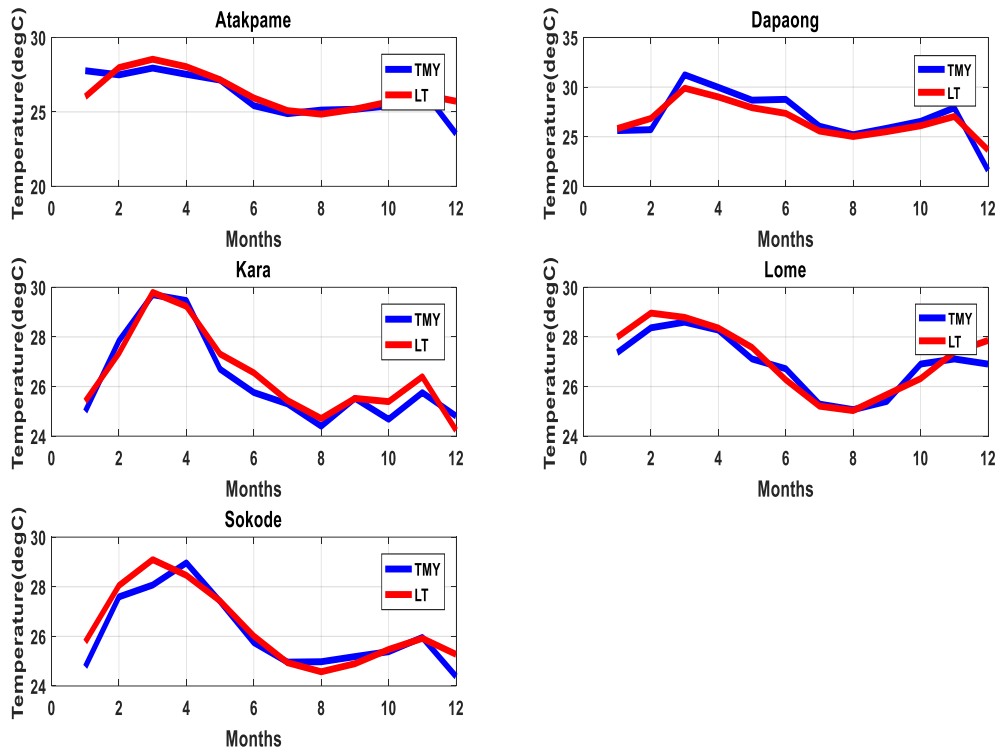


Figure 2-6: Mean temperature for the five locations

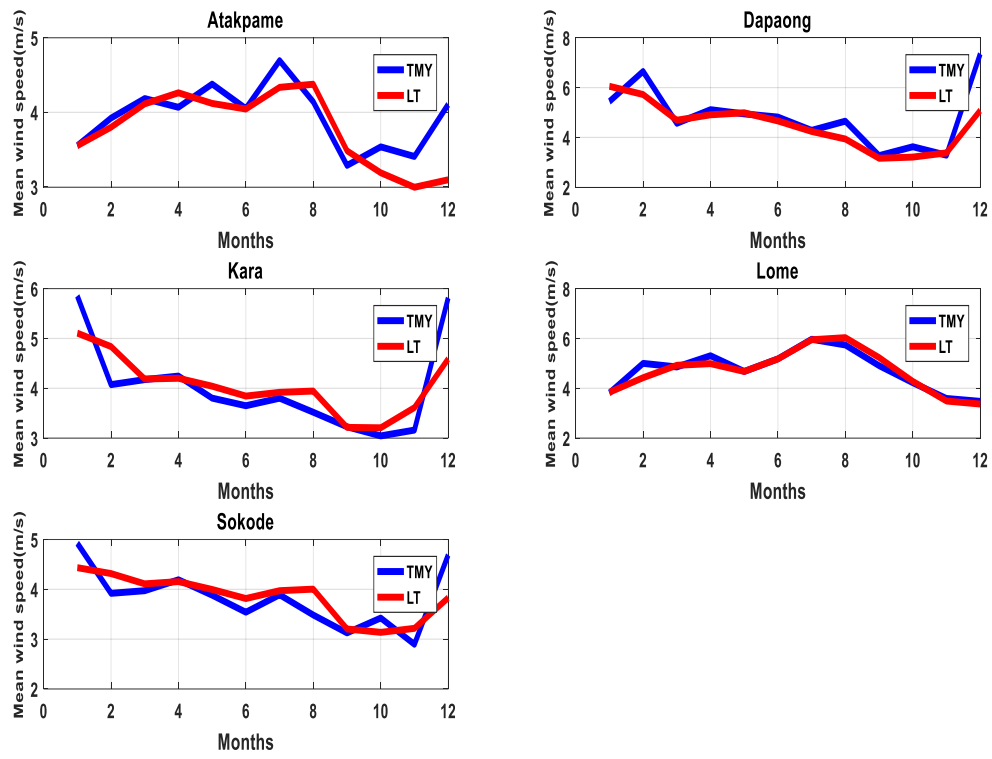


Figure 2-7: Mean wind speed for the five locations

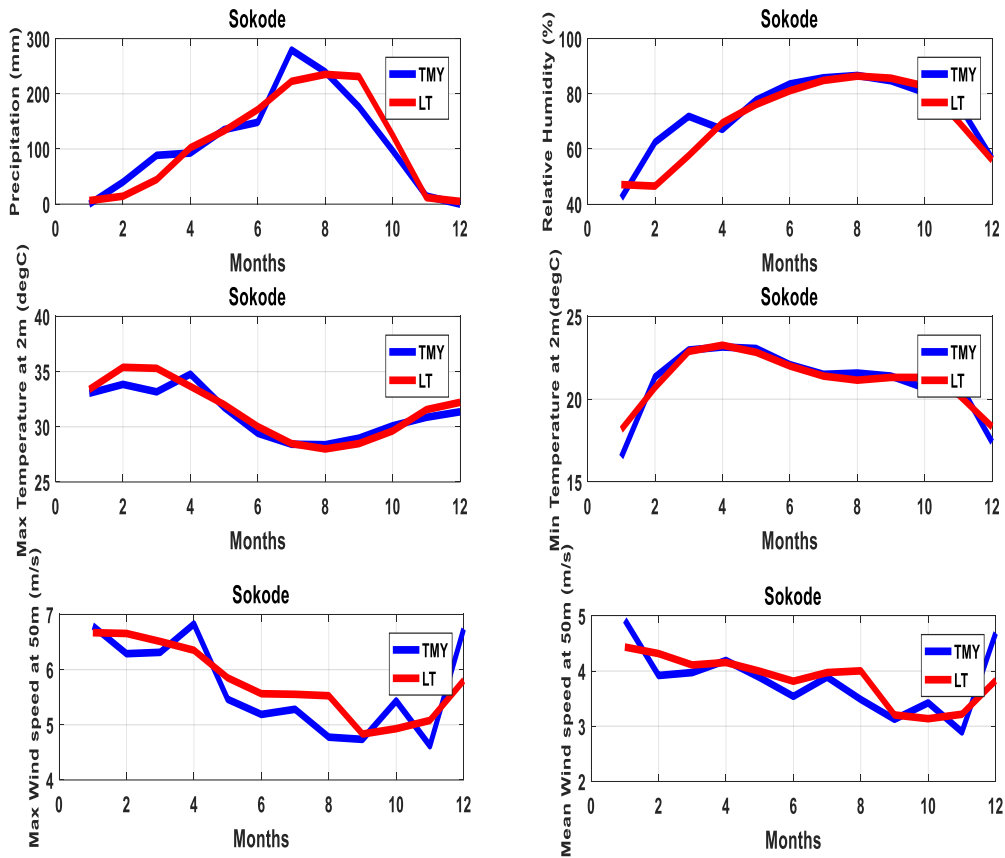


Figure 2-8: Other considered weather variables for Sokode

2.5.2 Performance of the PV System

The PV system's performance had been analysed under typical weather conditions of Sokode, the city chosen, as case study. Monthly PV system's output of 3 KW was simulated using the generated TMY and LT data. The results are reported in Figure 2-8. The curves associated to the two data were found to intently comply with the identical trend. Nevertheless, it can be discovered that the PV system generated less energy when using the TMY values than the LT data for the same year. The exceptions to the rule can be remarked for the months of February, April, June, July, August, September and November. The MPE varied between -10.62% in July and 9.11% in January. A value of -0.011% was obtained in February and August of the same year. The overall MPE of Sokode was -0.03%. On an annual basis, the power generated via the LT and TMY data were 1.486 MWh/kWp and 1.481 MWh/kWp, respectively. A surplus of 4.61 kWh in favour of the LT was achievable. Accordingly, it could be realized that the PV system underperformed when the TMY data were fed into the annual electricity simulator compared to the energy production based on the

LT mean values in Sokode. The overall RMSE values calculated for Sokode was 21.37 kWh, which represented 0.31%. The TMY data base also underestimated the PV's output in Atakpame and Lome with an MPE of 1.55% and 0.2%, respectively. In general, the RMSE calculated for the five aforementioned sites were 14.68 kWh (0.34%), 22.94 kWh (0.49%), 19.14 kWh (0.41%), 15.93 kWh (0.38%), 21.37 kWh (0.48%) in that order. Also, the PV system's performance, when TMY is fed in, was compared with existing experimental results.

An experiment was carried in 2019 under Lome actual conditions with two solar modules from different technologies: 1) polycrystalline silicon (pc-Si) and 2) amorphous silicon (a-Si) by (TCHAKPEDEOU, 2022). However, the technology r considered in the study is polycrystalline (MaxPower CS6X-320P). The results show that the energy produced monthly by the pc-Si technology varies between 117.55 kWh/kWp in June and 153.71 kWh/kWp in March while the a-Si technology production varies between 112.55 kWh/kWp in June and 146.45 kWh/kWp in March. The two technologies generated annually 1.67 MWh/kWp and 1.59 MWh/kWp in that order. Considering the PV system output simulation based on TMY data, the system's monthly energy generation varies between 88.03 kWh/kWp in June and 132.887 kWh/kWp in March with an annual production of 1.393 MWh/kWp. On the annual basis, the difference between the performance of the PV system output based on the TMY data and the two technologies under actual meteorological conditions in Lome in 2019 is 0.187 MWh/kWp and 0.007 MWh/kWp respectively. Accordingly, the TMY data could allow simulating of the pc-Si and a-Si PV systems output at 87.53% and 95% respectively.

Togo is granted suitable conditions for renewable energy production. The country is characterized by an insolation of 5.27 kWh/m²/day, 1,238.21 mm of average annual precipitation, and 7m/s of mean wind speed at 50m above the ground. However, clean energy represents a meagre percentage of hydropower and solar energy. A rigorous clean energy production planning strategy and a subsequent investment in the renewable sector under a favourable environment (political, social, ...) could accelerate a massive RE deployment across the country by increasing:

- a) Decentralized PV mini/micro-grid construction to supply rural areas,
- b) PV power plants a part from AMEA plant,
- c) Micro hydropower, as the country possesses potential sites, and
- d) Wind plant near the sea.

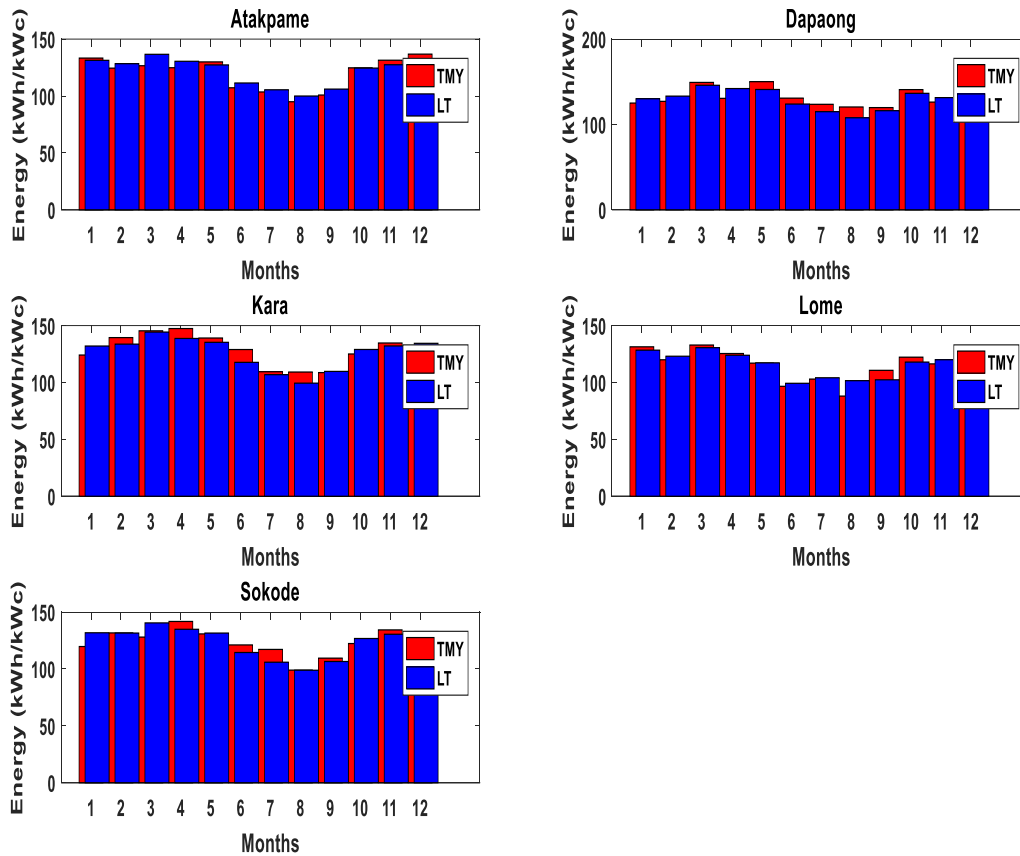


Figure 2-9: Monthly average energy produced by a grid-connected PV system for the five locations

2.6 Partial Conclusion - 1

RE penetration in the Togolese energy mix is still very low. Hydropower and solar energy are the main RE produced. With a complete set up capability of 360.02MW in 2020, 40.58MW (11.27%) was renewable out of which 6.48MW (1.8%) was solar and 34.1MW was hydro (9.47%). This study is intended to build up a clear climatic picture of the five most important cities in Togo: Atakpame, Dapaong, Kara, Lome, and Sokode. A typical meteorological year (TMY) data were generated for annual renewable energy output estimation and analysis. This approach serves as an alternative to provide solution for the missing weather data, which causes potential issues and barriers in the juvenile field of R&D. The TMY is a set of twelve months' data that without doubt describes most of the insolation patterns at the selected sites. For this study, the Sandia method was utilized due to its popularity and simplicity based on Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA-2) datasets. The study considered seven (7)

meteorological variables: 1) global solar radiation, 2) mean temperature, 3) maximum temperature, 4) minimum temperature, 5) precipitation, 6) relative humidity, and 7) maximum wind speed. The global solar irradiation was allocated with the most importance. The methodological process followed consisted of constructing the cumulative distribution function of the short and long-terms, the Finkelstein-Schafer statistics calculation, the weighting sums calculation, and the selection of the typical meteorological months to form the TMY. In addition, a PV system performance had been simulated using the generated TMY and the long-term average data (LT). Finally, the constructed TMY, the LT data, and the PV system output were subjected to the mean percentage error and the root mean square error analysis. As results, the TMY and LT were determined and presented a close variation under the weather conditions of the sites with a particular closeness in Sokode. The analysis of MPE and RMSE allowed to observe that the divergence between TMY and LT is quite better for global solar irradiation and mean temperature compared to other variables. This could be attributed to the importance given to each variable and their respective assigned weighting factors. In general, the PV energy system output based-TMY and the PV energy system output LT-based presented the same trend with a slight underestimation under the TMY data. The TMY data was able to predict the performance of the PV system to within 2% (<5%) for the long-term data in all the selected towns and to 0.85% in average. With the generated TMY weather variables, any government energy agencies, professionals, utility companies, and researcher in any of the chosen towns, may characterize the performance of their renewable energy systems before deployment. Therefore, the novel TMY permits not only an adjustment at the planning stage to be made, but allows also any future PV systems to be effectively sized in order to gain full benefit.

Chapter 3 Solar energy powered decentralized smart-grid for sustainable energy supply in low-income countries: analysis considering climate change influences in Togo

3.1 Partial Abstract - 2

A smart and decentralized electrical system, powered by grid-connected renewable energy (RE) with a reliable storage system, has the potential to change the future socio-economic dynamics. Climate change may, however, affect the potential of RE and its related technologies. This study investigated the impact of climate change on photovoltaic cells' temperature response and energy potential under two CO₂ emission scenarios, RCP2.6 and 8.5, for the near future (2024–2040) and mid-century (2041–2065) in Togo. An integrated Regional Climate Model version 4 (RegCM4) from the CORDEX-CORE initiative datasets has been used as input. The latter platform recorded various weather variables, such as solar irradiance, air temperature, wind speed and direction, and relative humidity. Results showed that PV cells' temperature would likely rise over all five regions in the country and may trigger a decline in the PV potential under RCP2.6 and 8.5. However, the magnitude of the induced change, caused by the changing climate, depended on two major factors: (1) the PV technology and (2) geographical position. Results also revealed that these dissimilarities were more pronounced under RCP8.5 with the amorphous technology. It was further found that, nationally, the average cell temperature would have risen by 1 °C and 1.82 °C under RCP2.6 and 8.5, in that order, during the 2024–2065 period for a-Si technology. Finally, the PV potential would likely decrease, on average, by 0.23% for RCP2.6 and 0.4% for RCP8.5 for a-Si technology.

3.2 Partial Introduction - 2

Energy is fundamental for the well-being of humans; it comes right after health, food, water, shelter, and welfare enhancement such as education, comfort, and sustainable environment (Akinyele et al., 2014; Akinyele & Rayudu, 2013; International Renewable Energy Agency, 2022; Wirschaft, 1999). Thus, energy will continue to vital to human beings for life to prosper on earth (Elavarasan et al., 2019; Madurai Elavarasan et al., 2020). As such, energy ought to handy to everyone under its various forms, and be affordable, reliable, and clean. Although electricity is a quintessential enabler of the UN Sustainable Development Goals (SDGs) (Santika et al., 2020), it is nonetheless a day by day challenge in some parts of the world. These electricity issues are exacerbated in developing countries, which adds to the destructive impacts of climate change (CC).

Therefore, decentralized energy assets (DER) such as renewable power (RE) may not only play an essential role in a nation's energy mix under present-day scenarios, but can additionally provide solutions to clean and reliable electricity supply to people, should the technology know-how continue to unfold (Elavarasan et al., 2020). Adding to that, the smart and DER applied sciences are turning environmentally pleasant and greater appropriate for integration into the future electric power network (Alotaibi et al., 2020; Speer et al., 2015). Today, the aforementioned electrical system is referred to as the smart grid (SG) (Ayadi et al., 2020; Clastres, 2011; EPRI, 2011; Wissner, 2011). A smarter electricity grid is robust, resilient and reliable, and can make certain the sustainability of the entire system (Anand S. Joshi, Ibrahim Dincer, 2010; Islam et al., 2014; Nobre et al., 2019; Nyasapoh et al., 2022; Oyedepo et al., 2018). This new kind of power grid was developed to overcome the weaknesses of the conventional electrical grid through the use of intelligent and net-metering techniques (Bayindir et al., 2016; Beidou et al., 2010; Konstantelos et al., 2016; Pooja & Ajmer, 2016). With the functionality of the SG to combine DER and allow electricity storage, RE-based electricity production is projected to increase throughout the world (Al-Shetwi, 2022; Al Haj Hassan et al., 2016; Kumar et al., 2020). Although RE is promising, some associated challenges, such as intermittencies, need to be overcome (Arnold, 2011; Begum et al., 2020; Beidou et al., 2010; Phuangpornpitak & Tia, 2013; Sinsel et al., 2019).

Photovoltaic (PV) electricity is made with the aid of a number of photo voltaic cells in a parallel and/or series connection. These cells convert the incoming sunlight into electrical energy based totally on the photovoltaic effect. More details regarding sunlight conversion into electrical energy can be found in (Ibram, 2015; Xiang et al., 2019). Three kinds of PV technologies (monocrystalline, polycrystalline, and thin film or amorphous) dominate today's world market. Each of the aforementioned technologies has distinctive features that make it special (Khursheed et al., 2019). The continuing impacts of CC in conjunction with the decline of fossil sources have given PV systems an important function in the worldwide energy mix. Hence, this globally growing share of PV systems influences tremendously all aspects of the electricity supply and demand chains. For instance, the supply system is transformed into a range decentralized systems nearer to people via grid-tied, stand-alone and hybrid systems, whilst the transportation device is redefined through the utilization of electric powered motors (Das, 2020; Ghenai & Bettayeb, 2019; Goel & Sharma, 2017). Interestingly, the capacity of PV systems reached 849 GW in 2021 worldwide. This installed capacity, equal to 28% of the world RE systems, has made PV the

quickest growing clean energy system (International Renewable Energy Agency, 2021). Concerning Togo, 6.48 MW of solar PV system was installed in 2020 (ARSE, 2020b). This share contributes to efficaciously bridging and/or enhancing socio-economic development through (1) increasing access to electricity and security, (2) climate change mitigation, and (3) decreasing environmental and health impacts (Litjens et al., 2018; Liu et al., 2020; Pillai et al., 2014; Raza et al., 2022; Srikranjapert et al., 2021). However, PV cells' efficiency is influenced by many factors, such as temperature, wind speed, insolation, clouds, and dust (A. Bonkaney et al., 2017; A. L. Bonkaney et al., 2017).

In that regard, studies have been undertaken in all aspects of research and development to apprehend the sustainability of energy systems, the nature of RE technologies and their integration into smart grids, limitations hindering their promoting and wide-scale deployment, and possible impacts from CC. The sustainable energy system is intently based on the smart grid and RE promotion, as proven in the literature. Islam et al. (Islam et al., 2014) performed an assessment of worldwide renewable energy-based electricity generation and smart grid systems for energy security and they pointed out that promoting RE ought to lead to sustainable energy. They justified their declaration through arguing that the smart grid can drive the RE-base electricity production to enhance electricity security and safety in the power system. Slootweg et al. (Slootweg et al., 2011) analysed smart grids—intelligence for sustainable electrical power systems. The results of their study supported the claim that the smart grid can make a contribution to the sustainable energy system. Likewise, Elavarasan et al. (Elavarasan et al., 2020), after conducting a holistic assessment of the present and future drivers of the renewable energy mix in Maharashtra State, India, stated that a sustainable energy sector may be enabled on the condition that a strong energy mix of RE is adopted. Anand et al. (Anand S. Joshi, Ibrahim Dincer, 2010) and Romer et al. (Römer et al., 2012) acknowledged the variability in RE-based electricity production due to the fact of weather conditions and proposed decentralized electricity storage to tackle it. In this regard, Basit et al. (Basit et al., 2020) claimed that storage systems can assist to reduce the challenges (power quality, reliability, power system stability, harmonics, sub synchronous oscillations, and reactive power compensation) that may additionally happen as an end result of RE integration onto the grid. Sathiyathan et al. (Sathiyathan et al., 2021) investigated multi-mode electricity converter topology for renewable energy integration with smart grids. They raised challenges in photovoltaic (SPV) systems in terms of low cell efficiency and solar panel output affected by the climate

conditions (solar irradiation and temperature) and proposed an alternative solution to manage and regulate the reachable power generated.

Furthermore, research on CC has been of great interest to the energy sector and climate scientists in many parts of the world, including West Africa. Hence, the authors studied the influence of CC on photovoltaic potential (PVP), wind density, hydropower, and concentrated solar power (CSP) at regional and continental level. The West African researchers investigated the influences of CC on RE assets throughout the region making use of climate models. Sawadogo et al. (2019) studied the impact of global warming on the PVP utilizing 14 different simulation models at a distance of 50 km resolution run under RCP 2.6 and 8.5 scenarios in West Africa. They focused on the deployment of monocrystalline technology. As a result, they discovered that CC may set off a reduce of 3.8% in PVP in any country in the region under the RCP8.5 scenario. This discount may additionally be possible even under a 3 °C increase in global warming. In the following year, they carried out a new study on the contemporary and future potential of solar and wind energy in Africa utilizing the Regional Climate Model version 4 (RegCM4) calibrated at a 25 km resolution. The outcomes of their study indicated a 2% decrease in PVP over the African continent in the mid-century under RCP8.5 (Sawadogo et al., 2020). Other authors investigated the impacts of future global warming on solar irradiance using RegCM4 driven by two global climate models (GCMs) at a 25 km resolution run under RCP2.6 and 8.5 (Patchali et al., 2020). This study was performed over five chosen Togolese cities across the five regions. The results revealed that there would be an upward in air temperature, whilst photo voltaic irradiance would decrease in the near future 2031–2060 and in far future 2070–2099.

It is well worth analysing the potential of RE beneath altering climatic conditions of a region or country. Unfortunately, the impact of CC on RE has yet to be assessed in Togo, much less the utilization of the RegCM4 CORDEX-CORE technique to examine this effect down to the 5 administrative regions. The Togolese RE potential and its decentralized power systems are presently affected by the local climate. Therefore, to better decipher the local impacts of CC on PVP in the whole country, and make contributions to placing conducive surroundings for decentralizing smart power systems to reap sustainable energy system, it is important to regionalize the utilization of the high-resolution model (RegCM4 CORDEX-CORE).

The government integrated solar energy into the energy mix to achieve 100% green power by 2030 through decentralized power systems such as grid-connected PV, photo voltaic mini-grids, solar kits, and solar public lights (Presidence togolaise, 2018). However, it is really worth pointing out that this policy may appear too bold and unrealistic due to the inherent variability of RE.

The main objectives of the study are to : (1) examine the impact of CC on three kinds of PV cells (Amorphous silicon(a-Si), Monocrystalline(Mono-Si), and Polycrystalline(Poly-Si)) in view of photo voltaic power plant installation across the country, (2) investigate the temperature variations due to CC and PV generation potential based on the RegCM4 CORDEX-CORE ensemble, (3) make use of 4 weather variables (solar irradiation, air temperature, wind speed at 10 m above ground, and relative humidity) to seek meaningful and conclusive results, and (4) study the effects of CC in Togo, as a whole, and then drill the research down to the administrative regions (a contribution to solar power project prefeasibility studies), as each has a specific climate.

Therefore, the study intends to make several contributions to the country and beyond.

First, the effects of CC on photo voltaic energy haven been investigated in Togo. The investigations have been further downscaled to each of the 5e regions to attain deeper insights. Hence, this scheme has shed more light on some regional discrepancies that have been until now more difficult to decrypt from the bigger picture, viz., impacts at the country level.

Second, the study filled in the gaps by analysing the impacts of CC on PV cell temperature, considering three types of cell technology (amorphous, monocrystalline, and polycrystalline) and the above-mentioned weather variables. An additional variable was the Togolese PVP, at large, broken down into its five administrative regions. Results were obtained via CORDEX-CORE.

Third, the study gave an effective picture of the Togolese administrative regions' weather conditions over the years. The understanding of this picture may help monitor the production of renewable energy for decades to come.

Finally, the knowledge of the present study could help not only to better select PV technologies, but also to enact green policy, taking into consideration the short and long-term climate interactions on RE.

3.3 Data and Methods

This section introduces the study area, clarifies the data, and elaborates on the methods. The datasets in query have been model-simulated data and has been derived from the Regional Climate Model version 4 (RegCM4). The approach was the energy rating methodology that gives the opportunity to estimate the PV potential based on the knowledge of the total insolation for a specific period, using a performance ratio (Bichet et al., 2019; Dubey et al., 2013; Jerez et al., 2015; Sawadogo et al., 2019, 2020). This method was preferred for the present work because the PVP is strongly dependent on weather variables. The approach could, therefore, serve as means to analyse the influence of climate change on PV technology.

3.3.1 Study Area

The land mass area under consideration is Togo. The country has five administrative zones: (1) Maritime, (2) Plateau, (3) Centrale, (4) Kara, and (5) Savannahs (Figure 3-1). Thus, the study focused on these five regions, as each has a unique climate. Togo is located in West Africa between 6° and 11° N latitude, and between 0°05' W and 1°45' E longitude.

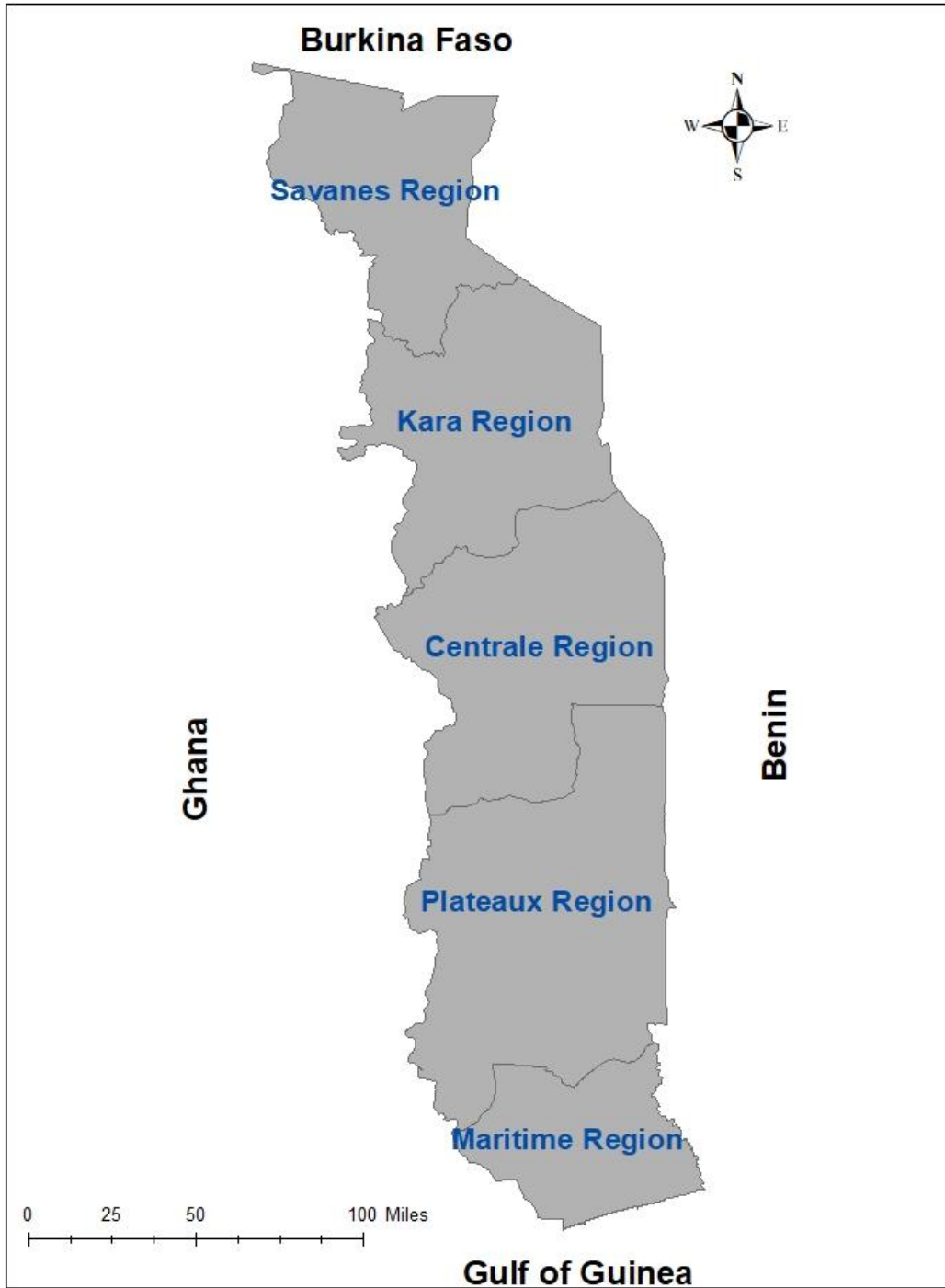


Figure 3-1: Togolese Administrative Regions

The total area is 56,600 km². The geographical position of regions and their areas are presented in Table 3-1.

Table 3-1: Geographic coordinates of the Togolese Administrative Regions.

Admin. Regions	Latitude		Longitude		Area (km ²)
Maritime	6°00'	6°50'	0°25'	2°00'	6100 km ²
Plateau	6°9	8°5'	0°30'	1°38'	16,800 km ²
Central	8°0	9°15'	0°15'	1°35'	13,317 km ²
Kara	9°20'	10°05	0°55'	1°25 E	11,738 km ²
Savannah	0°	1°	10°	11°	8533 km ²

3.3.2 Data

3.3.2.1 CORDEX-CORE Datasets and RCP Scenarios

The climate simulation data under consideration are from the Coordinated Regional Climate Downscaling Experiment-Common Regional Experiment (CORDEX-CORE) developed to guide local climate services (Remedio et al., 2019), as introduced in Table 3-2. CORDEX-CORE datasets function properly in relation to most CORDEX domains. They also represent well the climate sensitivity unfold in the CMIP5-ESM as highlighted in the literature (Coppola et al., 2021; Elguindi et al., 2014; Giorgi, Coppola, Jacob, et al., 2021; Giorgi, Coppola, Teichmann, et al., 2021; Sawadogo et al., 2020; Teichmann et al., 2021; Torres-Alavez, Das, et al., 2021; Torres-Alavez, Glazer, et al., 2021). The simulation's duration spans from 1970 to 2100 for two representative and concentrative pathways (RCPs): RCP2.6 (low GHG concentrations) and RCP8.5 (high GHG concentrations) (Moss et al., 2010).

Within the framework of this research, month-to-month Rs, Tas, Rh and Wspd at 10 m above the ground had been chosen as model data. The intervals 1976–2005, 2024–2040, and 2041–2065 had been chosen as reference period, i.e., near future and mid-century, respectively. Ensmean stands for a mean of a variable of the 9 models under CORDEX-CORE

3.3.2.2 Reference Datasets

Table 3.2 presents as well the reference data that had been regarded as as observation data.

The reference data used to evaluate the Rs dataset had been from the second edition of the Surface Solar Radiation Data Set-Heliosat Edition 2, SARA-2 (Pfeifroth et al., 2018). SARA-2 is a product derived from Meteosat satellites’ observations-based output on the visible channels of the MVIRI and the SEVIRI instruments used by means of countless researchers to evaluate solar irradiation generated from climate models (Bichet et al., 2019; Sawadogo et al., 2020; Tang, Morel, Wild, Pohl, Abiodun, Lennard, et al., 2019) due to the fact it exhibited low uncertainties and high accuracy (Boilley & Wald, 2015; Sawadogo et al., 2019). Monthly Rs had been retrieved from the CM-SAF platform for the length of 30 years (1986–2015).

In addition, month-to-month Tas, Rh and Wspd had been amassed from the ERA5 reanalysis product (Hersbach et al., 2019, 2020) for the duration of 30 years (1976–2005). The ERA5 data were had been used for their corresponding model datasets evaluation. ERA5 is concerned with new reanalysis and an advanced dataset in place of ERA-Interim. However, this remained a model to which some systematic biases had been attributed (Dullaart et al., 2020; Sawadogo et al., 2020; Tall et al., 2019; Wang et al., 2019).

Table 3-2:Model and observation datasets

Datasets	Description
Model Data Regional Climate Model version 4 (RegCM4): Ta, Rs, Wspd & Rh	Coordinated Regional Climate Downscaling Experiment-Common Regional Experiment (CORDEX-CORE) initiative (Remedio et al., 2019) Nested in three Coupled Model Intercomparing Project—Phase 5 (CMIP5) Earth System Models (ESMs) HadGEM2-ES (Collins et al., 2008; Martin et al., 2011) MPI-ES-MR (Giorgetta et al., 2013) NorESM-1 M (Bentsen et al.,

			2013; Iversen et al., 2013)
		25 km of the resolution	
Observation Data	SARAH-2: RS (1986–2015)	Satellite Application Facility on Climate Monitoring (CM-SAF), SARAH-2 (Pfeifroth et al., 2018)	
	ERA5 reanalysis: Ta, Wspd and Rh (1976–2005)	ECMWF’s fifth-generation reanalysis with a horizontal resolution of ~31 km (Boilley & Wald, 2015; Sawadogo et al., 2019)	

3.3.3 Methods

3.3.3.1 Flow Chart

The methodological approach adopted in this study is summarized in the flowchart presented in Figure 3-1.

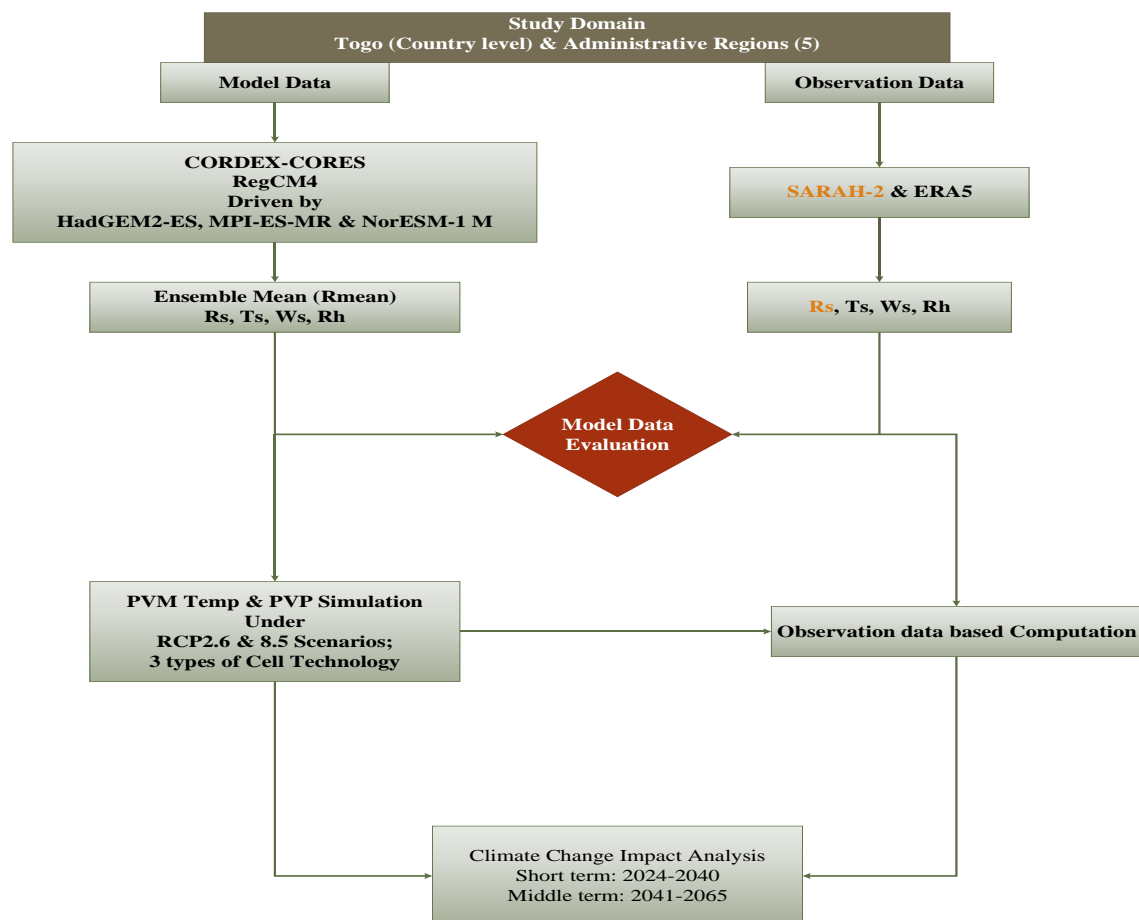


Figure 3-2 : Methodological flow chart.

3.3.3.2 Selection of Radiative Forcing Scenarios

In many parts of the world, governments, policies-makers, and energy and environmental agencies lack the dedication to combating CC. Togo is no exception to the rule, with no consistent policies enacted to date. This shortfall in energetic engagement has encouraged the choice of the RCP2.6 and 8.5. Thus, solely a dependable simulation strategy could help model the climate-change impact on renewable energy in Togo. RCP scenarios have been generally defined and documented in the literature (van Vuuren, Edmonds, et al., 2011). They are intended to project the concentration of atmospheric greenhouse gas (GHG) emissions.

At the global level, the goals of the RCP2.6 scenario can be succinctly stated as including, however not being confined to, the following:

- Based on the 2000 carbon emissions, a 4% reduction per annum is needed. The latter decrease can solely be achievable if the GHG reduction had been enhanced improved to about 5–6% annually.
- Increasing use of RE, nuclear, efficient-energy measures, carbon capture and sequestration, and bioenergy reduce sufficiently all major emission sources.
- Implementing new technologies for energy efficiency improvement.
- Limiting agricultural areas for food production employing high agricultural productivity.
- Elaborating sustainable standards for bioenergy production and management.
- Reducing appreciably non-CO₂ greenhouse gas emissions (van Vuuren, Stehfest, et al., 2011).

Furthermore, utilizing the RCP2.6 is probable to preserve the global temperature upward jostle at round 1.6 °C and well beneath 2 °C, respectively, by 2065 and 2100 (Gray, 2007).

Similarly, the RCP8.5 storyline simulates a global scenario. The conditions were such that:

- Energy demand will increase greatly due to the fact of unprecedented population growth,
- Little progress is made in terms of energy efficiency and conservation because of low socio-economic investments,
- International trade in energy and technology know-how is nonetheless limited, for this reason hindering any further social and technological progress,
- Future energy systems move toward coal-intensive technologies; these choices generate more GHGs.
- Strong environmental issues grow locally, especially in high- and medium-income regions.
- Food security becomes a quintessential issue, especially in low-income regions.
- Agricultural productivity increases steadily; thus, a healthful agricultural system is wanted to feed a growing population (Riahi et al., 2011; San José et al., 2016).

To sum it up, underneath the conditions described in the scenario RCP8.5, the global temperature would possibly amplify 2.6 °C and 4.8 °C through 2065 and 2100, in that order (Gray, 2007).

3.3.3.3 Simulation of PV Cell Temperature (PVct) and PV Generation Potential (PVGP)

Photovoltaic technology is green/clean at the point of application, silent, and environmentally friendly. The technology is comprised of many working parts—cells, modules, and arrays.

However, the output is heavily dependent on two main factors: (1) the PVGP and (2) the installed capacity. Therefore, the output is the product of the nominal installed power (Watts) by the PVGP. The latter potential is a dimensionless factor that accounts for the overall performance of PV cells as in contrast to their nominal power under certain weather conditions (Jerez et al., 2015). Various factors may additionally affect the magnitude of the PVGP. These variables range from local insolation, temperature, and season, to cells' efficiencies (Kafka & Miller, 2019). Thus, the PVGP is expressed as in Equation (3-1) (Jerez et al., 2015; Mavromatakis et al., 2010; Sawadogo et al., 2019).

$$PVGP(t) = P_r(t) \frac{Rs(t)}{Rs(STC)} \quad (3-1)$$

where $Rs(t)$ is the local shortwave radiation; STC is the standard test conditions under which $Rs(STC)$ is equal to 1000 W/m^2 ; $P_r(t)$ is the PV performance ratio (Jerez et al., 2015; Sawadogo et al., 2019).

This ratio is computed utilizing Equation (3-2).

$$P_r(t) = 1 + \gamma * [PV_{ct}(t) - T_{STC}] \quad (3-2)$$

where PV_{ct} is the PV cell temperature; T_{STC} is the ambient temperature set at $25 \text{ }^\circ\text{C}$ under STC ; and γ is $-0.5\%/^\circ\text{C}$.

It is really worth pointing out that crystalline cells' efficiency degrades in a hot environment at an average rate of about 0.4 to $0.5\%/^\circ\text{C}$ (Jerez et al., 2015; Sawadogo et al., 2019; Tonui & Tripanagnostopoulos, 2008).

Also, three technologies—Monocrystalline, Polycrystalline, and Amorphous—and four atmospheric variables— Rs , Tas , $Wspd$, and Rh —were considered. A negligible impact of wind direction had been noticed as in (WindDir) was assumed. Hence, PV_{ct} is modelled utilizing Equation (3-3) (TamizhMani et al., 2003).

$$PV_{ct}(t) = a + a_1 * Rs(t) + a_2 * Tas(t) + a_3 * Wspd(t) + a_4 * Rh(t) \quad (3-3)$$

where the regression coefficients a , a_1 , a_2 , a_3 , and a_4 are as presented in the Table 3-3 (TamizhMani et al., 2003).

Table 3-3: PV technology and corresponding PVct model regression coefficients.

PV Cell	a (°C)	a_1 (°C/W/m ²)	a_2	a_3 (°C/m/s)	a_4 (°C/Rh%)
Mono Si	1.57	0.0289	0.961	-1.457	0.109
Poly Si	3.9	0.030	0.954	-1.629	0.088
a-Si	2.5	0.026	0.964	-1.406	0.082

3.4 Results and Discussion

3.4.1 Model Data Evaluation

Figure 3-2 presents the ensemble mean (Ensmean) data reproduced by the model. These variables are wind speed (Wspd) at 10 m, solar irradiance (Rs), air temperature (Tas), and relative humidity (Rh) over the country.

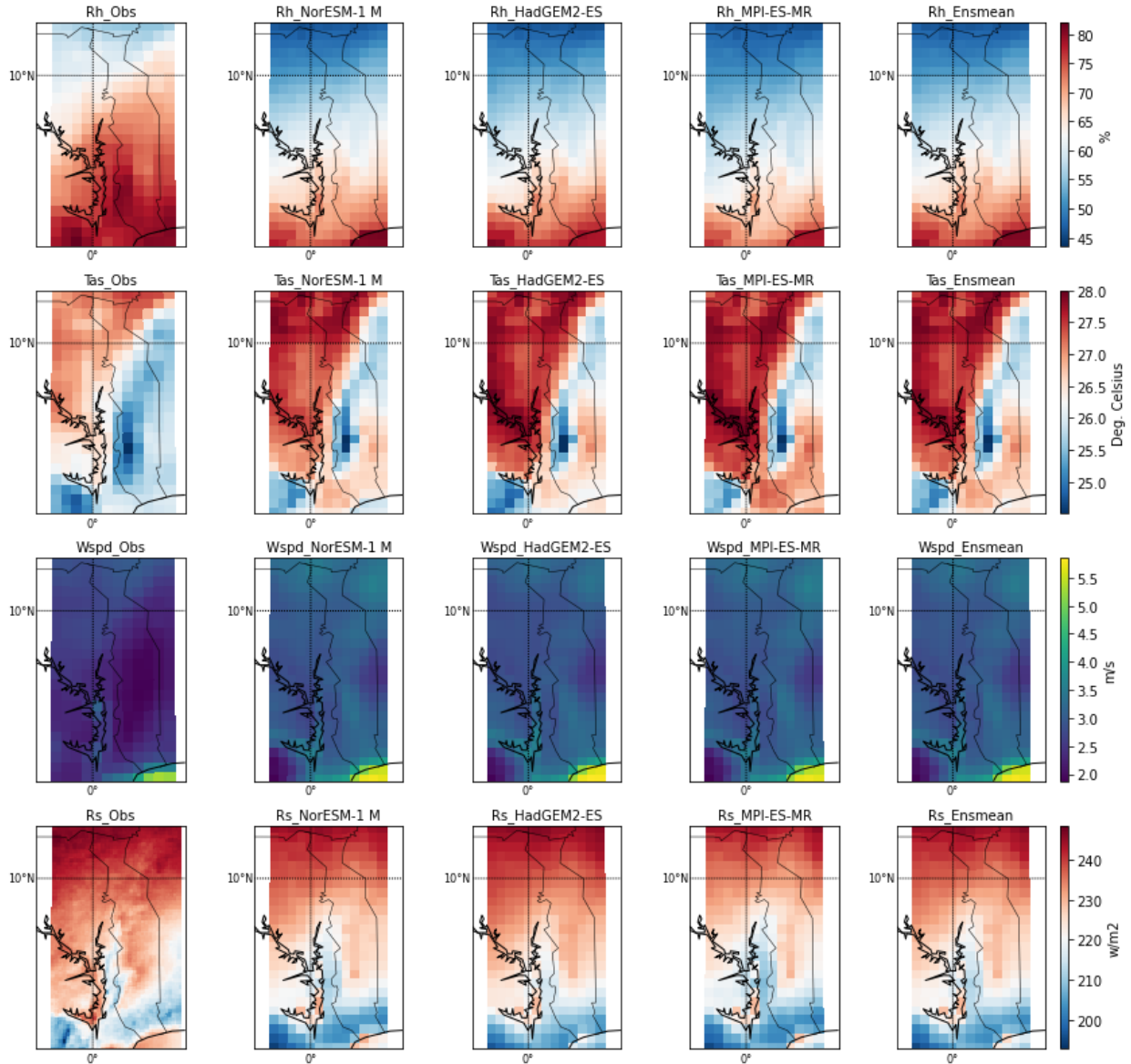


Figure 3-3: Rh, Tas, and Wspd at 10 m and Rs, in the present climate (1976–2005) of the RegCM4 driven by three ESMs (HadGEM2-ES, MPI-ES-MR, and NorESM-1 M) and its ensemble mean (Ensmean) between observation and simulations.

Rs, for instance, stands for the mean solar irradiance datasets of 9 consecutive models under CORDEX-CORE. The climatological correlation between the modelled and observed data is statistically significant at 95% as can be observed in Figure 3-3. However, this relationship varies from 0.91 in Wspd to 0.99 in Rh. The normalized standard deviation was 1.2 for Tas and 2.3 for Rs. In addition, the monthly observed spatial mean percentage deviation (MPD) performed by the Ensmean was -7.62% , -2.26% , -1.63% , and 12.39% , respectively, for Rs, Rh, Tas, and Wspd. It

can be seen that this MPD was relatively low. Overall, a low root mean square deviation (RMSD) was recorded, which spanned from 0.29 (Tas) to 17.23 (Rs). As observed, the model captured perfectly the latitudinal variations of the aforementioned meteorological variables. These findings were in agreement with the observations across the five regions. For example, a lower Rs is usually observed in the Maritime region, while a higher Rs is the norm in the Savannah.

On a distinctive note, the simulation was somewhat far from perfection, as it had some elements of bias as seen in Table 3-4. It is nicely acknowledged that simulations are primarily utilized to tune up performance, optimize processes, enhance safety, test theories, and so forth. As a result, the models underestimated the Rs, Tas, and Rh over the country; their respective average was 16.88 W/m^2 , $0.44 \text{ }^\circ\text{C}$, and 1.38% . In contrast, the model overestimated the Wspd by up to 0.44 m/s on average. Luckily, these results confirmed the findings of (Sawadogo et al., 2019, 2020). The model's underestimation of Rsds can be observed throughout across these 4 regions: Maritime, Plateaux, Central, and Kara. It is fascinating to point out that the underestimation of Rs declines from the Maritime region (South with 26.92 W/m^2) to Kara, which is situated in the Savanna (Its value was approx. 5 W/m^2). This type of phenomenon depicts a positive bias near the border with Burkina Faso (see Table 3.1 for details). This observation may be attributed to clouds and/or aerosols representation in the RCMs over the Gulf of Guinea and the SARA-2 data (France et al., 2013; Sawadogo et al., 2019, 2020; L. J. Wilcox et al., 2013, 2015; Wu & Fu, 2011). In addition, the bias related to Rsds could be linked to some difficulties in representing clouds in the model (Palmer, 2016; Solomon et al., 2009; Tang, Morel, Wild, Pohl, Abiodun, & Bessafi, 2019). The simulation of the Tas presents a positive bias across all regions, with a prevalence in the Savanna. Thus, Tas's bias over the country falls in the range of $0.4\text{--}10 \text{ }^\circ\text{C}$, as formerly reported (Sawadogo et al., 2020). On the different hand, Rh showed an increasing negative bias from South to North. The simulation of Wspd over the country was such that it exhibited a positive bias over the South Kara and Savannah regions. Then, a negative bias was revealed over the Plateaux and Central regions.

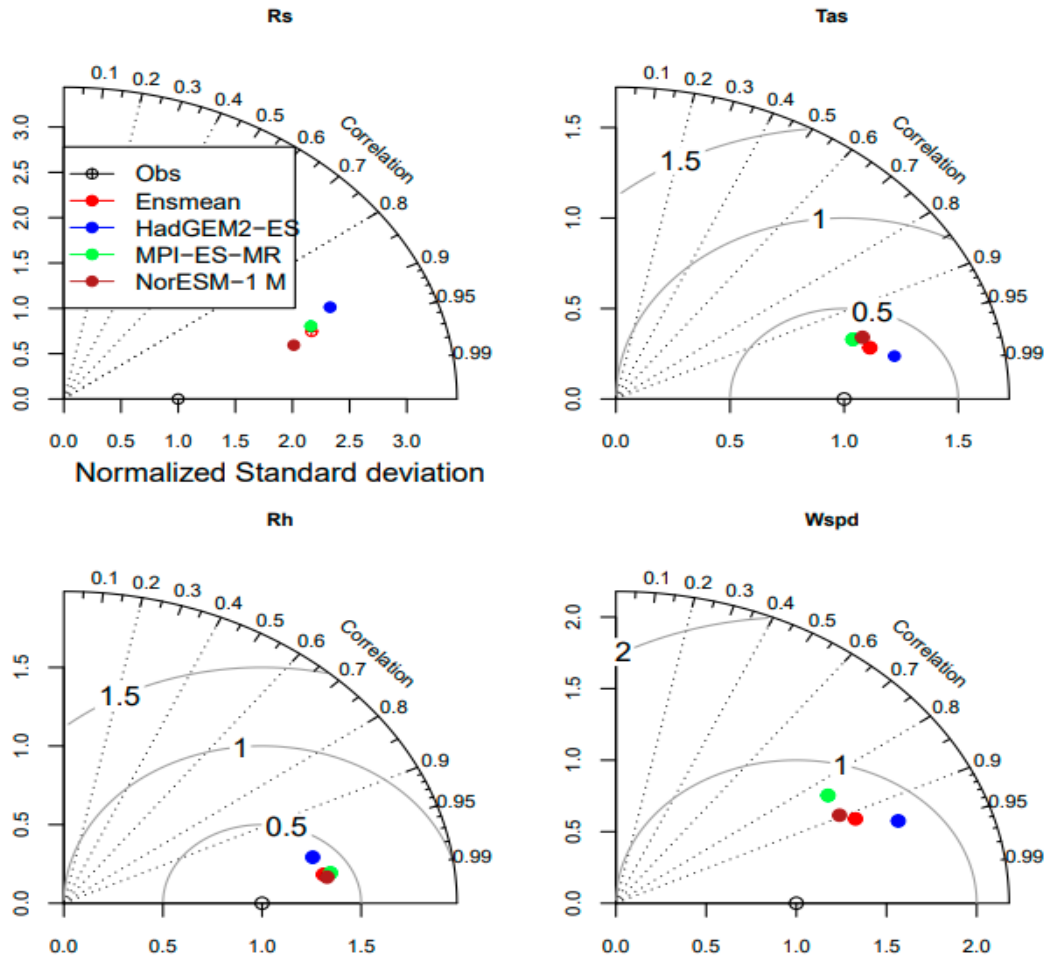


Figure 3-4: Taylor diagrams comparing the statistics (spatial correlation and normalized standard deviation) of Rs, Tas, Rh, and Wspd as simulated by RegCM4 and observation.

Table 3-4: Variables biases—Simulations vs. Observation.

Admin. Regions	R _s (W/m ²)	Bias _{Tas} (°C)	Bias _{Rh} Bias (%)	Wspd (m/s)	Bias
Maritime	-26.918	0.13	-5.31	0.877	
Plateau	-17.905	0.1289	-14.215	-0.10197	
Central	-12.0461	0.2406	-18.9988	-0.1329	
Kara	-4.992	0.009	-23.6915	0.1126	
Savannah	2.7692306	0.926079	-29.515	0.1907783	

3.4.2 Atmospheric Variables under RCP2.6 and 8.5 during the Near and Mid-Future

Under the mitigation pathway RCP2.6 and the worst-case CC scenario RCP8.5, atmospheric variables may fluctuate over the country. Thus, Figure 3-4 depicts that these variabilities were even more diverse in the administrative regions (see also Appendix 1).

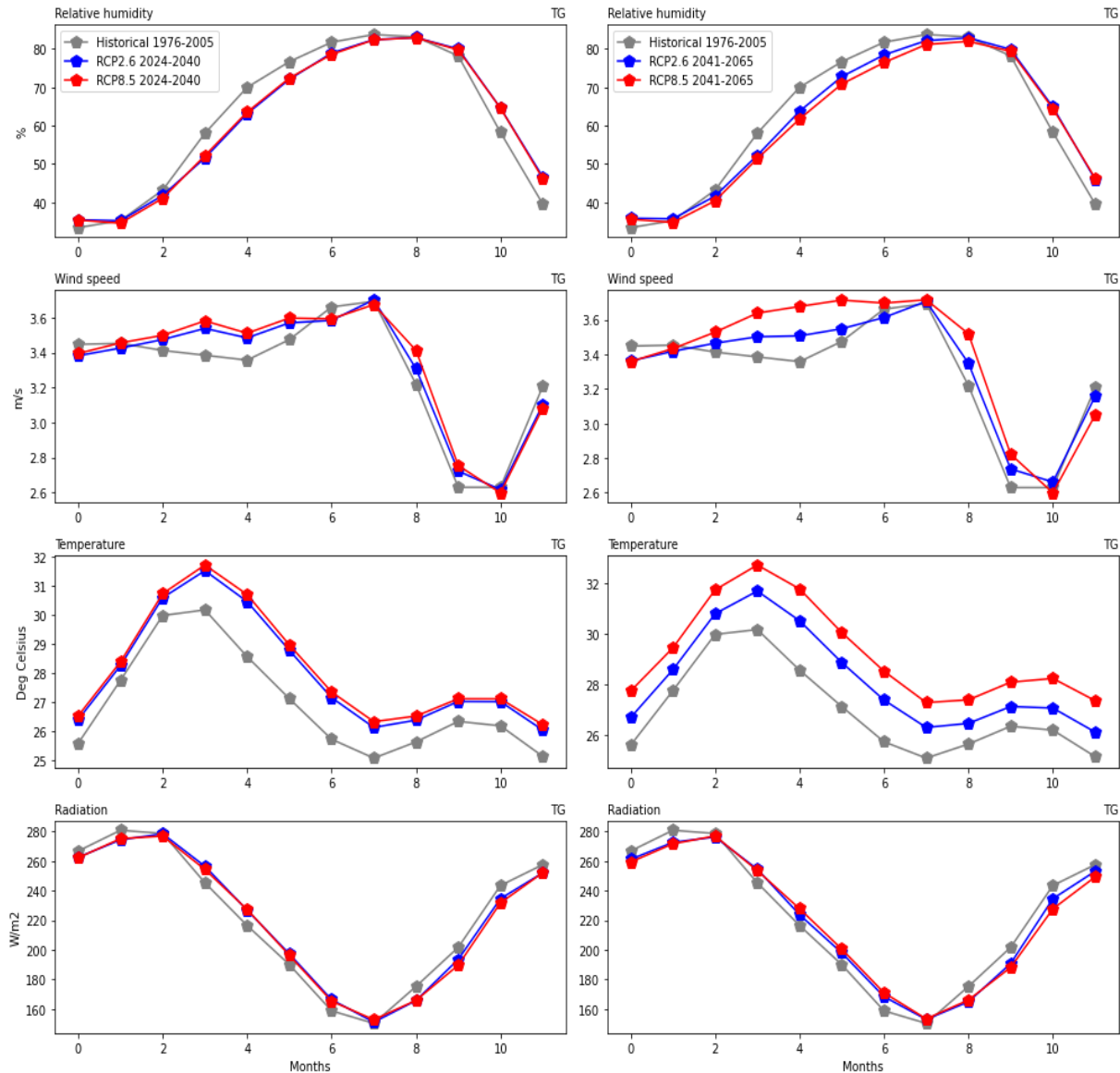


Figure 3-5: Climatological evolution of Rh, Wspd, Tas and Rs over Togo under RCP2.6 and 8.5 scenarios during 2024–2040 and 2041–2065.

Figure 3-5 portrays their climatological variations. The scenarios disclose a decrease in the monthly Rh over the country. Under RCP2.6, a 0.53% monthly average decrease was achieved between 2024 to 2040 and 0.41% less during 2041–2065. Likewise, beneath RCP8.5, Rh would

be impacted. Rh declines by approx. 0.63% and 1.39% on average, respectively, during 2024–2040 and 2041–2065. Conversely, Wspd is projected to barely increase at a rate of 0.03–0.04m/s for RCP2.6 and 0.05–0.1 m/s for RCP8.5 in the near future and mid-century. Similarly, Tas would rise at a monthly rate of 1.04–1.19 °C for RCP2.6 and 1.2–2.25 °C for RCP8.5 over study periods under scrutiny. However, Rs may decrease at a rate of 0.48–1.18 W/m² (RCP2.6) and 1.3–1.65 W/m² (RCP8.5) during the near future and mid-future.

The general overview of the country suggests mild changes over the regions (Figure 3-6). In summary, Wspd and Tas would increase, whilst Rh and Rs decrease under the scenarios. The decline in Rs seems significant over the southern region (Maritime); this could be caused by more reflection of incoming shortwave radiation due to high concentration of aerosols in the atmosphere resulting from intense activities of growing population and industries near the coast. A contrasting phenomenon was, however, observed concerning the Rs over the Central and Kara regions. This scenario divulges that Rs would increase on an average of 0.029 W/m² and 0.14 W/m² at the end of 2024 and 2040, in that order.

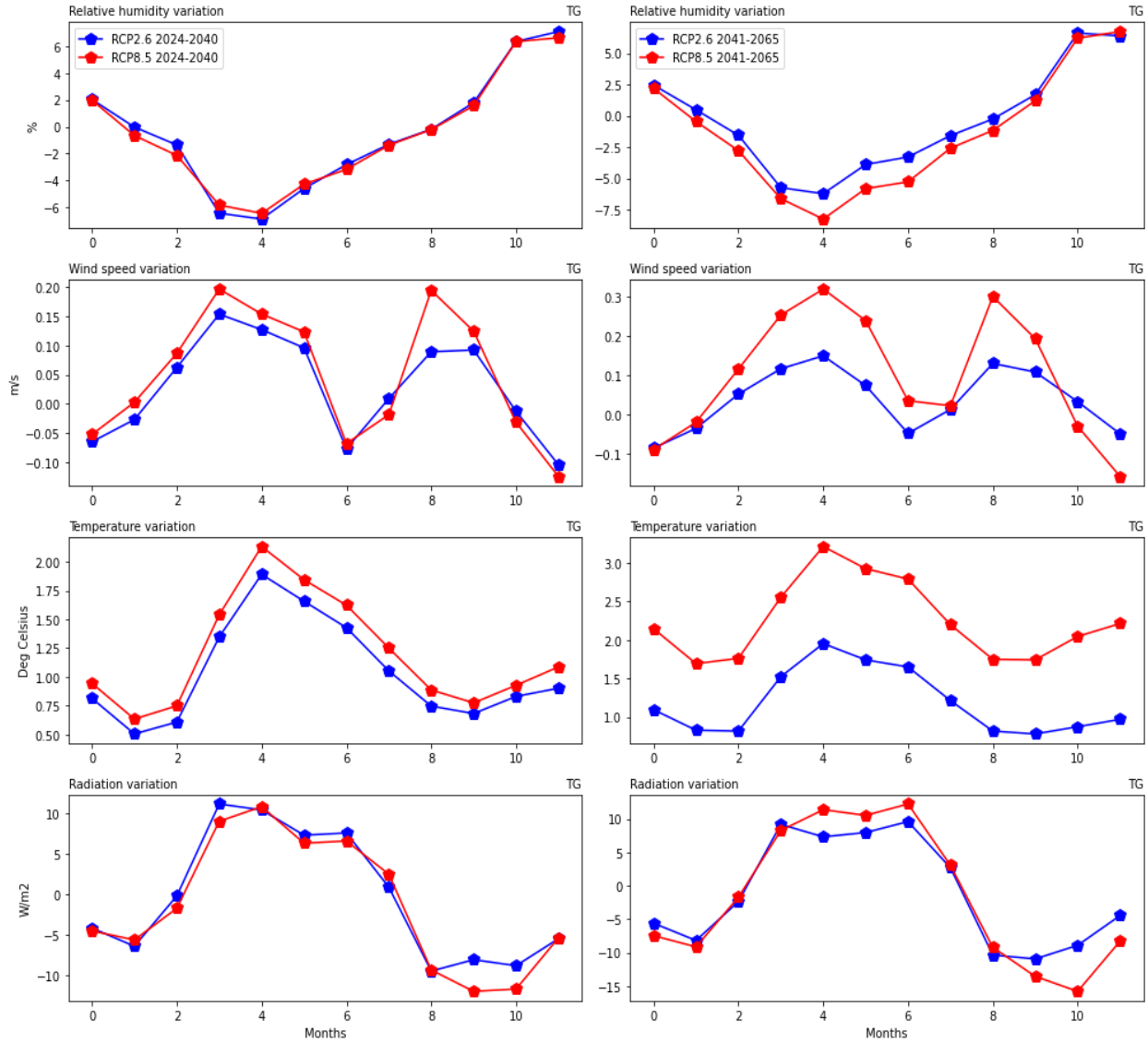


Figure 3-6: Climatological variation of Rh, Wspd, Tas and Rs over Togo under RCP2.6 and 8.5 scenarios during 2024–2040 and 2041–2065.

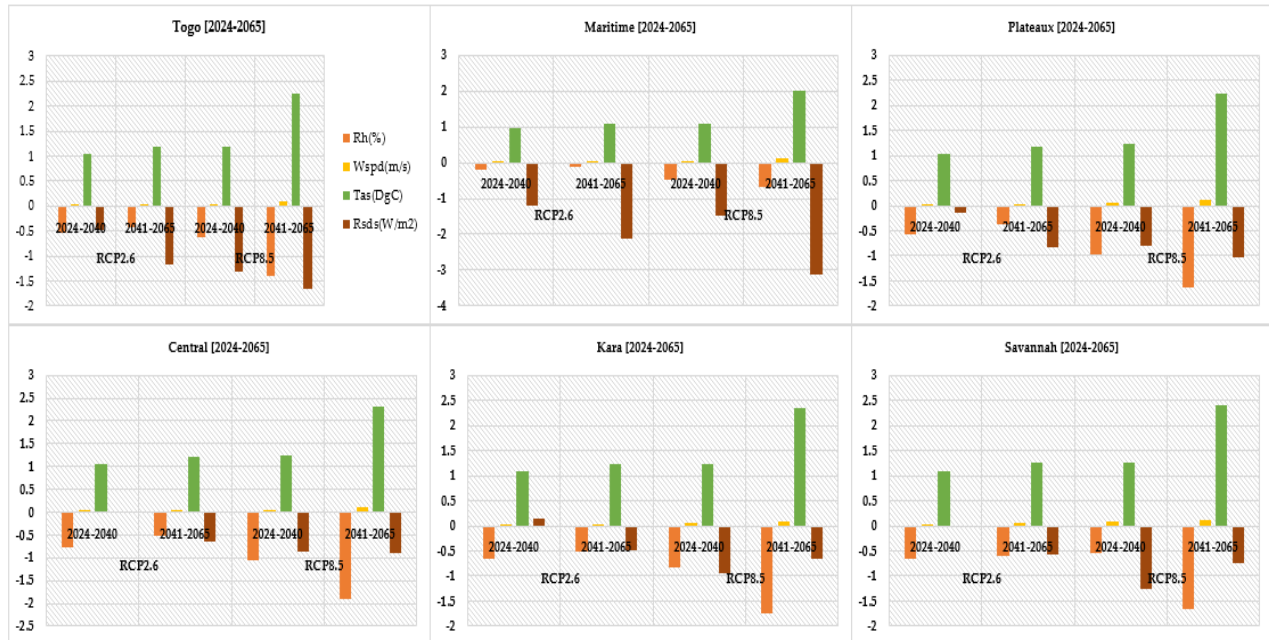


Figure 3-7: Climatological mean variation of Rh, Wspd, Tas and Rs over Togo under RCP2.6 and 8.5 scenarios during 2024–2040 and 2041–2065.

3.4.3 Projected PVct and PVGP Variations Following Cell Technology

3.4.3.1 Projected PVct Changes over Togo

Figure 3-7 describes the annual spatial and temporal changes of the PVct from the present day to the mid-century (2065) under the RCP2.6 and 8.5. The climatological evolution, together with the RCP scenarios and cell technologies (a-Si, Mono-Si, and Poly-Si), were also analysed. The results showed an increasing cell temperature over the near future (2024–2040) and mid-century (2041–2065). This growth was solely dependent on the radiative forcing as well as on the technology in question. The temperature variation would likely rise from March to July and September to December, compared to the reference period. In short, PV cells’ temperature would rise even further under RCP8.5 than under RCP2.6. This eventuality could be attributed to the cell’s inherent nature and the geographical location of the country.

Moreover, it was observed that the temperature rises more for the amorphous than the two other counterparts. It was further remarked that the temperature has grown slightly more for monocrystalline than the polycrystalline-based cell. These discrepancies are portrayed in Figure 3-8a. Moreover, these variations were found to have a strong correlation with the monthly insolation, with an average of 1 °C, 1.01 °C, and 1.03 °C under RCP2.6, respectively; and 1.81 °C,

1.82 °C, and 1.88 °C under RCP8.5 in that order. Again, the estimation period is 2041–2065, and the technologies under study are Poly-Si, Mono-Si, and a-Si. It remains a known fact that PV cells’ efficiency decreases with a rise in ambient temperature. Astonishingly, an exception was noticed in the Maritime region, where the amorphous cell showed a slight increase compared to the mono and poly. See Figure 3-8b for more details. On a different note, the absence of sound mitigation and adaptation strategies, at a global scale, towards a greener environment and economy, would hinder any real RE efforts. Furthermore, narrowing the evaluation to the administrative regions, the findings revealed that the variation of the cells’ temperature was different (see Appendix 2).

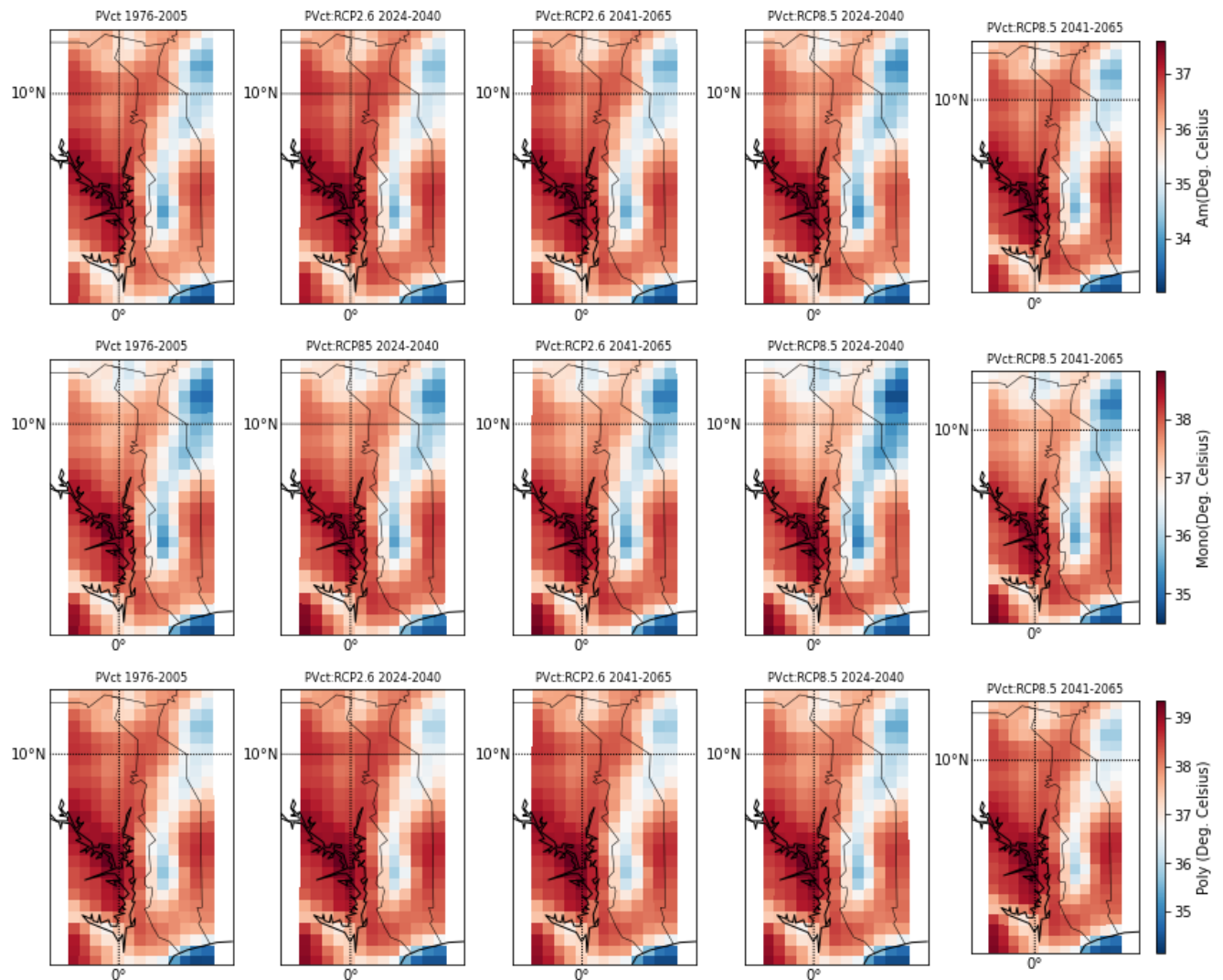


Figure 3-8: Estimated annual and spatial PVct variations, Togo.

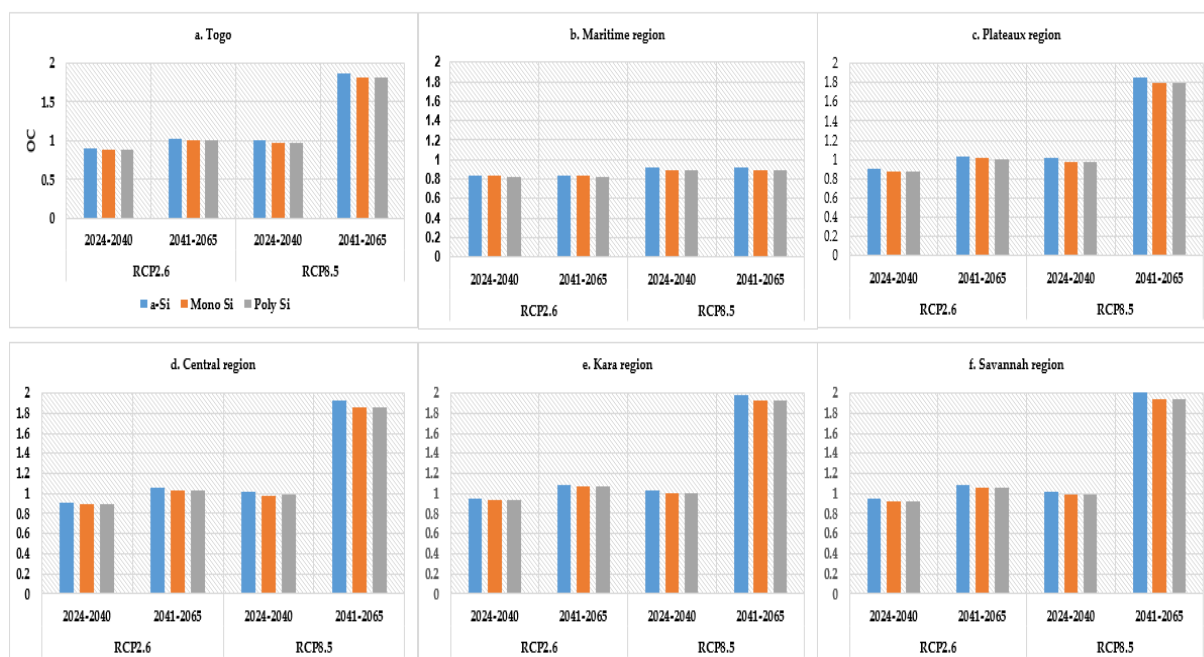


Figure 3-9: Monthly mean cells' temperature under RCP2.5 and 8.5 and technology, Togo.

3.4.3.2 Projected PVct Changes over Maritime Region

Figure 3-8 shows the monthly mean cells' temperature, under RCP2.5 and 8.5, and the three technologies in query over the administrative regions and country at large. The climatological variations, as well as the monthly mean variations of the PVct, are presented in Figure 3-8b, with to cell technology. Cells' temperature rise was found to be low in the Southern regions compared to the rest of the regions. This discrepancy was likely caused by the seasonal breeze. Thus, the average rise in monthly cells' temperature was projected to be 0.82 °C, 0.83 °C, and 0.84 °C for Poly-Si, Mono-Si, and a-Si, in that order, under RCP2.6. Similarly, these variations were found to be 0.89 °C, 0.9 °C, and 0.92 °C for Poly-Si, Mono-Si, and a-Si, respectively, under RCP8.5. Again, the simulation duration spans from 2041 to 2065.

3.4.3.3 Projected PVct Changes over the "Plateau" Region

The Plateau lies within the Gulf of Guinea. As a result, it has a very dense woodland where trees can grow up to 18.4 m. It is also very mountainous with the highest mountain in the country, Mount Agou (986 m above sea level). Over the Plateau, the yearly simulations of the PVct, as can be observed in Figure 3-8c, and its climatological variations to the cell technology, were analysed. A monthly cell temperature rise was found to be 1.0 °C, 1.01 °C, and 1.03 °C for Poly-Si, Mono-Si, and a-Si, in that order, under RCP2.6. An increase of about 1.74 °C, 1.80 °C, and 1.85 °C was

observed for Poly-Si, Mono-Si, and a-Si, respectively, under RCP8.5. Note that the simulation period is as stated above, viz., 2041 to 2065. The increase will possibly be lower beneath poly-Si, medium under Mono-Si and high in a-Si technology over the region.

3.4.3.4 Projected PVct Changes over the Central Region

The central region straddles the Gulf of Guinea and the tropical Soudanese zone. This region is essentially mountainous with the Tchaoudjo massif, Malfakassa, Faza, and Barba-Bassar mountains. It experiences two rainy and dry seasons yearly. The monthly average variation in cells' temperature is presented in Figure 3-8d. As can be observed, the increase in PVct was projected to be 1.02 °C, 1.03 °C, and 1.05 °C for Poly-Si, Mono-Si, and a-Si, respectively, under RCP2.6. In addition, the temperature changes were 1.862 °C, 1.856 °C, and 1.92 °C for Poly-Si, Mono-Si, and a-Si, in that order, under RCP8.5. The aforementioned simulation period was kept the same. It is worth to point out that the rise in PVct for the Poly-Si is slightly higher in contrast to Mono-Si during the near and mid-future under the RCP8.5.

3.4.3.5 Projected PVct Changes over Kara Region

Kara is composed of valleys, plains, and Plateaus. This region hosts an old rugged massif, extending to Benin and Ghana borders. Figure 3-8e presents the monthly mean projection of the rises in PVct. On the one hand, the latter increase was estimated at 1.067 °C for Poly-Si, 1.069 °C for Mono-Si, and 1.09 °C for a-Si under RCP2.6. On the other hand, the PVct increased to about 1.93 °C Poly-Si, 1.926 °C for Mono-Si, and 1.99 °C for a-Si under RCP8.5. For both cases, the simulation spans from 2041 to 2065. Likewise, the Poly-Si exhibited the same performance as in the Central region but differed from that of the Maritime region. Conclusively, the temperature rises of the Poly-Si were slightly higher than those of the Mono-Si.

3.4.3.6 Projected PVct Changes over the Savanna Region

Savannah is the driest part of the country and has a tropical Soudanese climate. It has just two main seasons—the rainy season and the dry season—per year. The climatological variation of the PVct over the year for the three cell technologies was succinctly analysed. The magnitude of the observed variations differed, not only monthly, but also across years. These changes were even more pronounced if anthropogenic-based pollution is factored into the study. Temperatures continue to increase drastically at a global level for RCP8.5. Figure 3-8f portrays the projection of PVct rise over the Savannah during the near and the mid-century. The findings show that the

monthly mean rise would be 1.05 °C for Poly-Si, 1.06 °C for Mono-Si, and 1.08 °C for a-Si under RCP2.6. The temperature change will likely be 1.942 °C, 1.945 °C, and 2.0 °C for Poly-Si, Mono-Si, and a-Si, in that order, under RCP8.5 during the mid-future. The trend in the PVct rise was somewhat comparable to that in the Southern region. These outcomes point out that the rise would be lower for Poly-Si, medium for Mono-Si, and greater for a-Si technology.

3.4.4 Projected PVGP Changes over Togo and Its Administrative Regions

3.4.4.1 PVP Projected Changes over Togo

Figure 3-9 portrays the yearly spatial and temporal variations of the PVGP from 2024 to 2065 under the RCP2.6 and 8.5 over the country. These variations depend on the type of cell technology, as seen in the figure. Hence, the PVGP was projected to vary throughout the country due to CC. The variabilities may be contingent on seasons. Further, the monthly average PV potential shrunk significantly per annum under the RCP8.5 scenarios. Long-term estimates revealed a PVGP reduction for Poly-Si, Mono-Si, and a-Si of 0.14%, 0.15%, and 0.15%, respectively, underneath the RCP8.5. The study also disclosed a PVGP rise of 0.22% for Poly-Si, 0.23% for Mono-Si, and 0.23% for a-Si under the RCP2.6 scenarios. The aforementioned analysis was performed for the periods 2024–2040 and 2041–2065, in that order, as viewed in Figure 3-10.

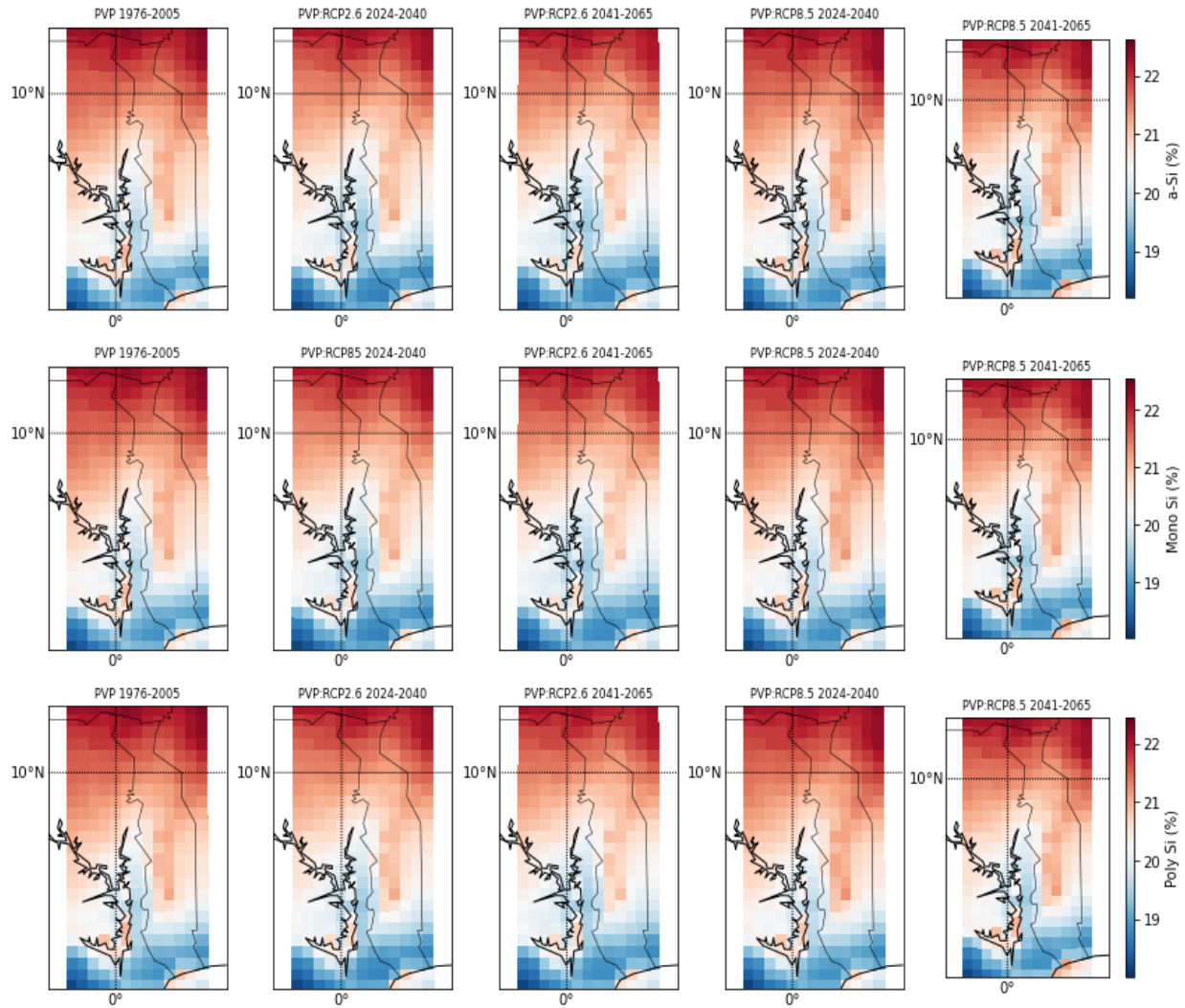


Figure 3-10: Projected annual and spatial changes in PVP in Togo under RCP2.6 and 8.5.

The reduction under RCP8.5 would turn out to be 0.23% for Poly-Si, 0.23% for Mono-Si, and 0.23% for a-Si all through 2024–2040. Finally, these reductions would be 0.36%, 0.36%, and 0.37% for Poly-Si, Mono-Si, and a-Si, respectively, for the duration of 2041–2065. A close observation helps recognize that the reduction in the case of Poly-Si technology would be lower in contrast to Mono and Amorphous. This change in photo voltaic electricity production potential due to climate change varied across the regions (see Appendix 3).

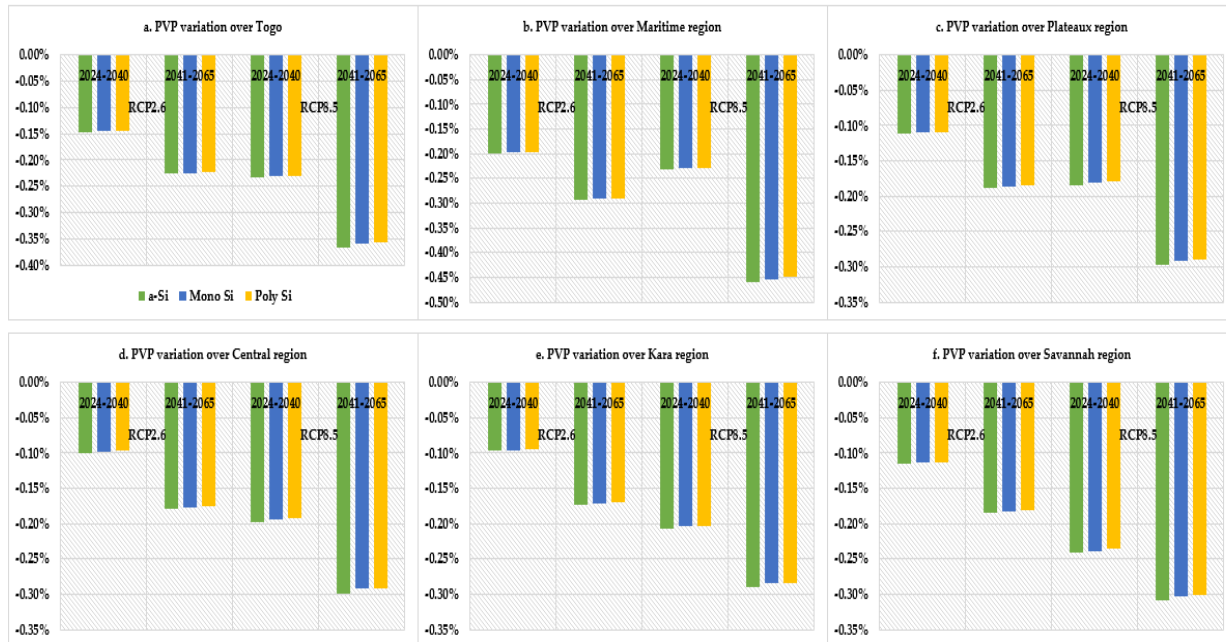


Figure 3-11: Monthly average reduction in PVP from 2024–2065 under RCP2.6 and 8.5 scenarios over Togo for a-Si technology.

3.4.4.2 Projected PVGP over Maritime Region

This study estimated the influences of CC on the PVP alongside the coastal region. The simulations forecast a yearly reduction in PVP irrespective of the PV cell technology. Therefore, the CC-induced reductions under the RCP2.6 scenarios were 0.195% for Poly-Si, 0.197% for Mono-Si, and 0.199% for a-Si over 2024–2040. As time goes on, this reduction worsens. Thus, the long-term catalysed reductions, viz., for 2041–2065, were, respectively, 0.29%, 0.292%, and 0.295%.

Under the worst-case CC, i.e., RCP8.5, the reduction would likely extend over the region. The estimated reductions were 0.228% for Poly-Si, 0.229% for Mono-Si, and 0.232% for a-Si in 2024–2040. Likewise, the situation in the region continues to worsen even more. Hence, the forecast changes were 0.450%, 0.453%, and 0.459% for Poly, Mono, and Amorphous, in that order, for the mid-future (2041–2065). Under this scenario, the reduction induced in a-Si was the largest, as can be observed in Figure 3-10b.

3.4.4.3 Projected PVGP over the Plateau Region

This section describes the impact of CC on solar energy production over the Plateau. Results showed a continuous shrinkage in the regional PVGP, as time unfolds. Moreover, the reduction in PVGP, modelled by using CORDEX-CORE, closely depended on PV cell technology. Thus, the

simulations, under the RCP2.6 scenarios, yielded an average monthly reduction of about 0.11% for each cell technology from 2024 to 2040. Simulations additionally showed, for the period 2041–2065, that the reductions were 0.185% for Poly-Si, 0.187% for Mono-Si, and 0.189% for a-Si. However, under the worst-case CC scenarios (RCP8.5), the reductions would likely increase over the region. Additionally, the cut was uniform for all three technologies. This cut was 0.18% from 2024 to 2040. The results also pointed out that the cuts were 0.29% for Poly-Si, 0.29% for Mono-Si, and 0.30% for a-Si in 2041–2065. Thus, the induced-cut in a-Si was the highest, whilst Poly-Si exhibited the least, as viewed in Figure 3-10c. All things being equal, the CC impacts on PV technology would be more pronounced in the Southern region than in the Plateau.

3.4.4.4 Projected PVGP over Central Region

Similarly, the impacts of CC on the PVGP were analysed for the Central region. It is worth pointing out that the aforementioned three technologies were tested under the same conditions. Surprisingly, the cut in PVGP was the same for all three technologies, but different per scenario. Hence, this CC-induced-reduction, under the RCP2.6 scenarios, was projected to be 0.10% in 2024–2040, while it became 0.18% in 2041–2065.

Nevertheless, under the worst-case CC scenario (RCP8.5), the reduction would likely increase over the region. These cuts were 0.19% for Poly-Si, 0.19% for Mono-Si, and 0.20% for a-Si in 2024–2040. The changes, then, increased to 0.29%, 0.29%, and 0.30% for Poly, Mono, and Amorphous, respectively, in 2041–2065. The reduction induced in a-Si was projected to be the highest, while that of Poly-Si was the lowest, as seen in Figure 3-10d.

3.4.4.5 Projected PVGP over Kara Region

CC impacts on PVGP have been investigated in Kara region. The outcomes indicated a reduction in the PVGP over the years. The technologies under scrutiny were Poly-Si, Mono-Si, Amorphous. Under the RCP2.6 scenarios, the projected reductions were uniform across the technologies. This cut was 0.10% in 2024–2040 and 0.17% in 2041–2065.

Nevertheless, under the worst-case climate change scenarios (RCP8.5), the reduction in PVGP would possibly increase. According to the projections, the cuts in PVGP had been 0.20% for Poly-Si, 0.20% for Mono-Si, and 0.21% for a-Si in 2024–2040. These cuts then would likely become 0.28%, 0.28%, and 0.29% in 2041–2065, respectively, for the Poly-Si, Mono-Si, and a-Si. A close

observation divulged an induced-PVGP reduction for a-Si to slightly dominate, while the PVGP of Mono-Si was projected to stay medium, as seen in Figure 3-10e.

3.4.4.6 Projected PVGP over Savannah Region

Sound know-how of the PVGP is essential to precisely estimate the electricity generation capacity of the three technologies under investigation, viz., (1) Poly-Si, (2) Mono-Si, and (3) a-Si. It was found that the CC would negatively impact the above-mentioned cells installed in Savannah. Under the RCP2.6 scenarios, the reductions in PVGP had been 0.11%, 0.11%, and 0.12% for Poly-Si, Mono-Si, and a-Si, respectively, in 2024–2040. For the mid-future, i.e., 2041–2065, this PVGP cut became 0.18%, irrespective of the cell in question.

However, underneath the worst-case climate change scenario (RCP8.5) the reduction would all likelihood amplify in Savannah. Thus, a uniform cut of 0.24% was estimated for all the cells in 2024–2040. In contrast, under the RCP8.5, the mid-future cuts were 0.30%, 0.30%, and 0.31% for Poly-Si, Mono-Si, and Amorphous), respectively, in that order. Finally, the triggered reduction in a-Si would slightly dominate, as viewed in Figure 3-10f.

3.4.5 Comparative Analysis

A growing interest is noticed in modern times in developing countries to decentralize the socio-economic sector on one hand. On the other hand, tremendous efforts are put in place to diversify the energy generation mix. The Togolese economy is no exception. It is embarking on a transformative journey to cut down its GHG emissions through investing in clean and green energy. Hence, new transformative industries are encouraged through tax-cut and other incentives to be implanted in the South. Similarly, new power plants are planned to be commissioned far from the capital city, however close to the load-centres to ensure an effective minimization of transmission costs. Therefore, it is of great significance to analyse the picture of each administrative region of the country under the CC-based scenarios. This investigation could help control the production of clean and renewable power. Throughout this study, CC was proved to significantly impact RE resources and its related technologies.

Under the current study, it was understood that the impacts of CC on solar energy projects in Togo gave an average overview of the situation for a long time to come (see Appendix 6). Therefore, the findings shed light on the bigger picture that could be observed at a regional scale as succinctly depicted in Table 3-5 (see also Appendix 4 & 5). Though a locality may fall inside a specific zone,

such as Guinea, Soudanese, and Sahelian, with fairly uniform characteristics, morphology, topography, and climate conditions, features vary from one locality to another.

At the regional scale, CC's impact on PV cell temperature and solar energy production varied across the Togolese regions. From the projections, these variations depended solely on (1) RCP scenarios, (2) cell technology, and (3) region. See Figure 3-11 for extra details. There would be a likely rise in cell temperature and a reduce in PVGP underneath all the climate scenarios in the course of 2024–2065 throughout all the administrative regions. The rise in PVct may be more pronounced following a-Si technology and much less with Poly-Si underneath both of the RCP2.6 and RCP8.5 scenarios over the five regions. Accordingly, the increase in PVct would likely result in a PVGP decline over the regions. The Poly-Si-based technology appears to likely be more resilient followed by the Mono-Si based under the altering climate impacts over the years, under the Togolese climate conditions.

The PVct may rise on average at a rate of 0.82°C over the Maritime region to 1.07°C over Kara under the RCP2.6, and at a rate of 0.89 °C over the Maritime region to 1.94 °C over the Savannah under RCP8.5 if the Poly-Si technology is considered from 2024 to 2065.

The PVGP was projected to decrease with a rate of –0.1% over Kara to –0.3% over the Maritime beneath RCP2.6. The PVGP was additionally forecast to decline at a rate of –0.18% over the Plateau to –0.45% over the Maritime under RCP8.5 if Poly-Si was considered for the period 2024–2065.

In general, over the country, the average rise in the cell temperature would be between 0.88 °C to 1 °C and 0.97 °C to 1.82 °C during 2024–2040 under RCP2.6 and 8.5 concerning Poly-Si and a-Si, respectively. In addition, the average decrease would possibly differ from –0.14% to –0.226% under RCP2.6 and –0.23% to –0.4% under RCP8.5 for Poly-Si and a-Si, in that order, over the country.

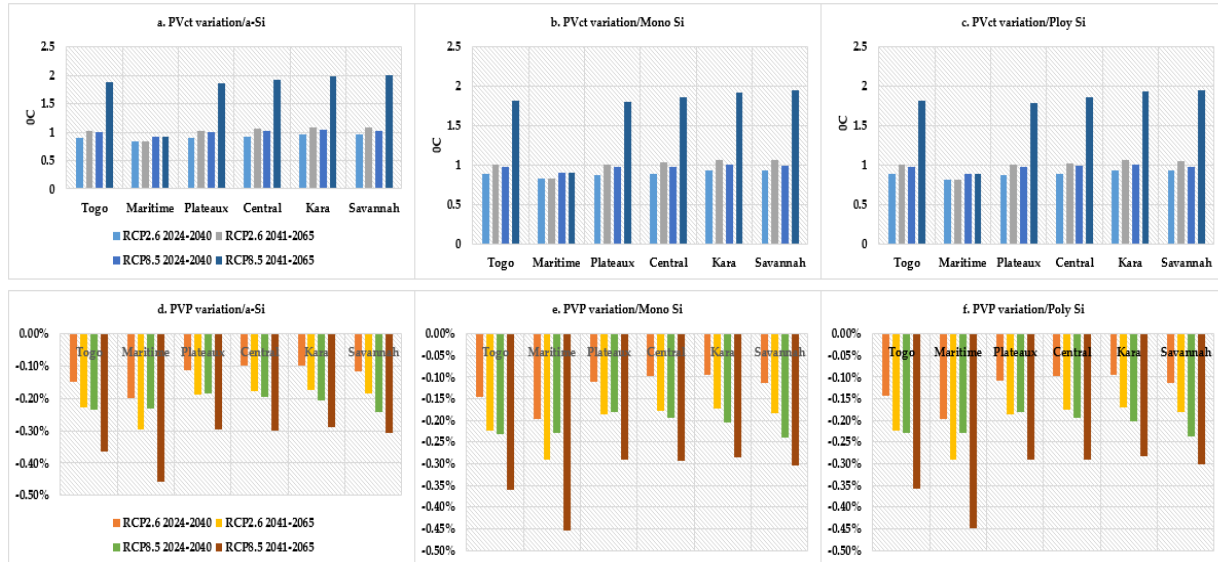


Figure 3-12: Summary of climate change on solar energy (PVct and PVP) under RCP2.6 and 8.5 as a result of PV cell technology usage 2024–2065 (near and middle futures).

Table 3-5: Highlights of impact of CC on PVct and PVP over Togo and its Administrative Regions.

Rise in PV Cell Temperature from 2024–2065				Decrease in PV Potential from 2024–2065			
Domains	Min	Max	Scenarios (RCP)	Domains	Min	Max	Scenarios (RCP)
TOGO (°C)	0.88 (poly-Si)	0.3 (a-Si)	2.6	Togo (%)	0.14 (poly-Si)	0.3 (a-Si)	2.6
Regions (°C)	0.82 (poly-Si) over Maritime	1.09 (a-Si) over Kara	2.6	Regions (%)	0.095 (poly-Si) in Kara	0.3 (a-Si) in Maritime	2.6
TOGO (°C)	0.97 (poly-Si)	1.88 (a-Si)	8.5	Togo (%)	0.22 (poly-Si)	0.37 (a-Si)	8.5
Regions (°C)	0.89 (poly-Si) over Maritime	2.01 (a-Si) over Savanes	8.5	Regions (%)	0.18 (poly-Si) in Plateaux	0.45 (a-Si) in Maritime	8.5

3.5 Partial Conclusion - 2

The long-term shifts in temperature and weather patterns, also known as climate change (CC), have inflicted extreme socio-economic losses to the global economy. These economic forfeitures are so unprecedented that an evaluation of their influences on renewable energy potentials is necessary. This study investigated the impact of CC on photovoltaic cell temperature (PVct) and

photovoltaic generation potential (PVP), considering three PV-cell technologies (i.e., amorphous, monocrystalline, and polycrystalline), under the Togolese local weather conditions. The Regional Climate Model version 4 (RegCM4), licensed by the CORDEX-CORE initiative, was utilized. Hence, possible social and environmental impacts have been investigated for the period 2024–2065 under two climate scenarios—a low radiative forcing (RCP2.6) and a high radiative forcing (RCP8.5). Consequently, the PVct would likely rise, while the PVP would decrease during the period 2024–2065 under the two scenarios (RCP2.6 and RCP8.5). These variations depended on three main factors, specifically the (1) climate scenario, (2) PV cell technology, and (3) geographical location (regions) of the country. The magnitude of the triggered variation was found to be more pronounced under the scenario RCP8.5 for amorphous cells. The PVct would plausibly rise from 1.03 °C to 1.88 °C, whilst PVP would likely decrease by 0.23% and 0.37% under RCP2.6 and 8.5, respectively, for a-Si technology. Regionally, the magnitude of these impacts would most possibly amply from the South (Maritime region) to the North (Savanes region), regardless of the scenarios and PV cell technologies.

This study gave evidence that the outputs of solar PV plants would likely to be undermined by the consequences of CC. Therefore, based on these findings, it is recommended that for decentralized solar power systems (viz., grid-tied, energy storage systems, mini-grid, and micro-grids), policy-makers, investors, and energy planners need to factor in the effects of CC in the following activities: (1) feasibility studies, (2) frequency of maintenance and monitoring, (3) planning for alternative solutions, and (4) responding to sudden changes in power stability and reliability. Finally, emerging nations—Togo and neighbouring countries—are urged to develop a green energy policy to mitigate CC.

Chapter 4 : Modeling of Togolese Power System in View of Smart Grid Implementation

4.1 Partial Abstract - 3

Addressing today's power-related issues and providing reliable and secure electricity in developing countries require transforming the existing power systems. This study is, therefore, carried out to comprehend the factors that most weaken power companies in emerging countries. Moreover, the study attempted to model and simulate power systems with Simscape-MATLAB/Simulink in order to implement a smart grid. The Togolese power system was investigated as a case study. This power system was analyzed based on the expert elicitation scheme. Results showed that issues triggering the Togolese power system included limited supply, discrepancies in policies and regulations, technical issues regarding the transmission, distribution, and off-grid subsystems, limited investment, and lack of incentives and rebates. Furthermore, Togolese power had been modeled and could be used as a precondition for the power transformation process. Accordingly, an oriented-based model for resilient power systems was proposed for the transformation of the aging power infrastructure of emerging economies.

Keywords — power systems; modelling; power plants; national network interconnected; Simscape, transformation.

4.2 Partial Introduction - 3

Economic and population growth are driving energy demand at the national and global levels (Huang et al., 2018; Zarfl et al., 2015). Hence, electricity demand is increasing at an unprecedented rate and outpaced the growth of power system installations. This discrepancy is much more pronounced for centralized than decentralized power generation systems (Zambroni de Souza & Castilla, 2018). Therefore, the aforementioned scenario is not suitable to address today's power-related paradigm, such as high demand, limited access, power outages, aging infrastructures, security and reliability issues, and extreme climate change events. To meet the increasing demand, utility companies are extending their power generation capacity, which is mostly fossil-fuel based. Because of the depletion of conventional energy resources in addition to being responsible for a major part of greenhouse gas (GHG) emissions, decentralized energy systems are nowadays thought to play a key role in providing the necessary energy to balance consumption at all levels. Unfortunately, the existing power system was not designed to enable the massive integration of

decentralized renewable resources (DRR). In addition, fossil fuel-based energy production is not only unsustainable but is also highly detrimental to the environment. Moreover, due to lesser ethics, lesser regard for best practices, and scanty resources, the power systems of emerging countries could be viewed as being very unsustainable compared to that of the developed economies (Bolton & Foxon, 2015). Consequently, immense renewable energy penetration onto the grid may increase the existing energy-balance requirements at all levels of the system (Math, H.J. B., 2, Jin, Z., Francisc, Z., Jan, M., Alex M., 2010). Thus, the current power system needs to be transformed to accommodate a high penetration of DRE onto the electrical grid. Improving the power system has been of significant interest to researchers (Mamandur & Chenoweth, 1981) and (Arya et al., 2015) through demonstrated control algorithms of, respectively, how voltage profiles and power quality (harmonics elimination, load balancing, and voltage regulation) can be improved. Most renewable energy systems, such as solar, wind, and tide, are highly intermittent because the period that electricity can be generated is limited. It is commonly admitted in scientific community that RE is not reliable. It is worth pointing that reliability is not a function of a single generation system, but rather a result of how the whole power system operates. Nevertheless, the reliability of wind power can be improved by a Model-based Fault Detection and Fault to Tolerant Control (Habibi et al., 2019). As for solar energy systems, its performance may be improved through: 1) frequent cleaning, 2) proper IR scanning and monitoring, 3) utilization of a tracking system, 4) management of vegetation around the system, and 5) use of highly efficient PV/CPV technology (Yamaguchi et al., 2017). Furthermore, it is documented that the quality and reliability in transmission and distribution systems could be improved by 1) installing PV system (Bouhouras et al., 2010), 2) using a distributed power-flow controller (Ramesh & Reddy, 2012), 3) using predictive models (Agüero et al., 2009), and 4) applying a reconfiguration method (Bashardoust et al., 2016; Mishra et al., 2017; Nazerian et al., 2018; Yadaiah et al., 2016). Studies on the power system, particularly in developing countries, have been rare. By using existing discoveries and expert knowledge, it has been possible to highlight fundamental critical points in the power system transformation to fill the gap. The present study attempts to bridge the gaps, utilizing the Togolese power system for illustration purposes. Based on expert elicitation, the methodology entailed a thorough assessment of the power sector and the Togolese power systems has been modelled based on Simscape-MATLAB/Simulink for the purpose of smart grid implementation. A proposal for

smart grid development roadmap and fundamental changes that would enhance power quality and reliability in the country and beyond have been discussed.

The following section details the methodology of the current study. Section 2 discusses the overview of traditional and smart grids. Section 3 presents the methodology. Section 4 presents the results and discussions. Section 5 presents the smart grid roadmap and the changes to be implemented. Finally, the conclusion is presented in section 6.

4.3 Overview of traditional grid and smart grid

4.3.1 Traditional electrical grid system

Four major components constitute the electrical system under the traditional grid (TG) that include electricity production plants, transmission substations, distribution substations, and end users (Gao et al., 2012; NIST, 2012). Its structure is described in Fig.4-1. Based on energy resources, power is produced and transported at high voltage to be distributed at medium and low voltages to the end users. Residential appliances access the power through meters.

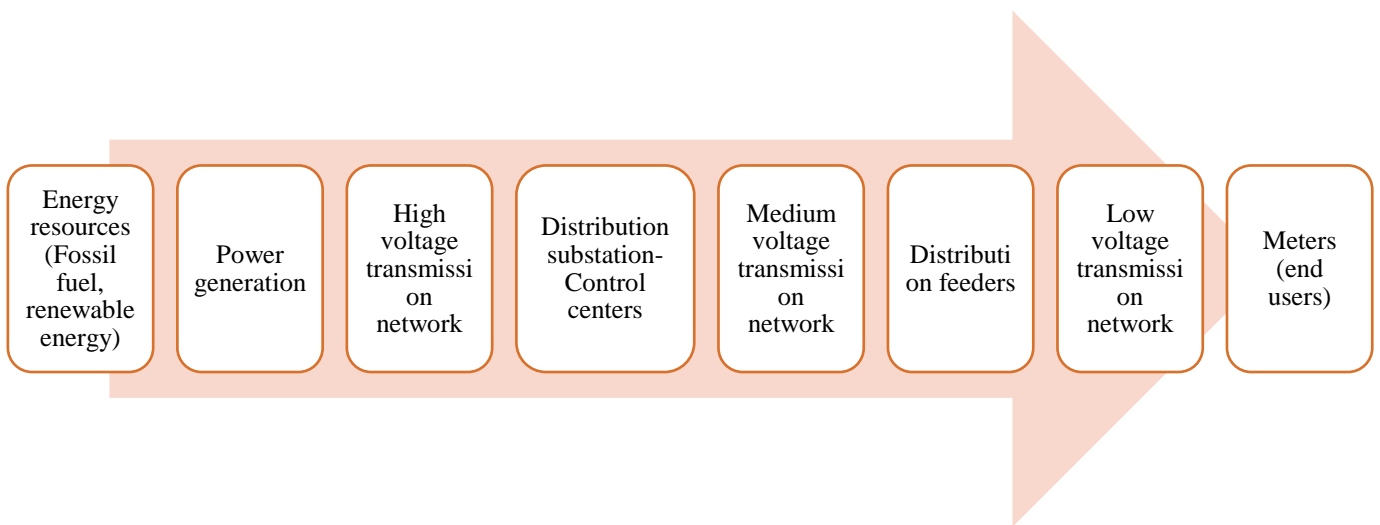


Figure 4-1:Electrical system overview

In a traditional power system, electricity production is centralized. About 59% of energy production is wasted as heat, 6 to 8% is lost along the transmission and distribution lines and only about 20% of its production capacity reached the consumers (Biabani et al., 2011; Zareen et al., 2012). Furthermore, many limitations are hampering the old system from being robust and efficient. Some of the weaknesses of the traditional power system include the following:

- i. Aging of the infrastructures (power networks are half a century old),
- ii. Power flow is in one direction only that says from supply to demand,
- iii. System operation depends on historical data and experience,
- iv. Operators detect overloading system,
- v. Lack of flexibility to incorporate new distribution generation,
- vi. High power loss,
- vii. High maintenance costs,
- viii. Likely events of costly power interruption and power outage,
- ix. Deficit of situational awareness,
- x. Defective visibility,
- xi. Lack of automated analysis, and
- xii. High Equipment failure (Zareen et al., 2012).

Considering the growing demand of the present economies, it is obvious that traditional grid is out of phase and no more reliable (Zareen et al., 2012).

4.3.2 Smart grid (SG)

SG is an electrical network that can intelligently integrates generators and consumers to efficiently deliver safe, economic, reliable, efficient, and sustainable electricity supplies (Phuangpornpitak & Tia, 2013; Vijayapriya & Kothari, 2011). An SG does so with help of its innovative capabilities shown in monitoring, controlling, communication, and self-healing aspects to:

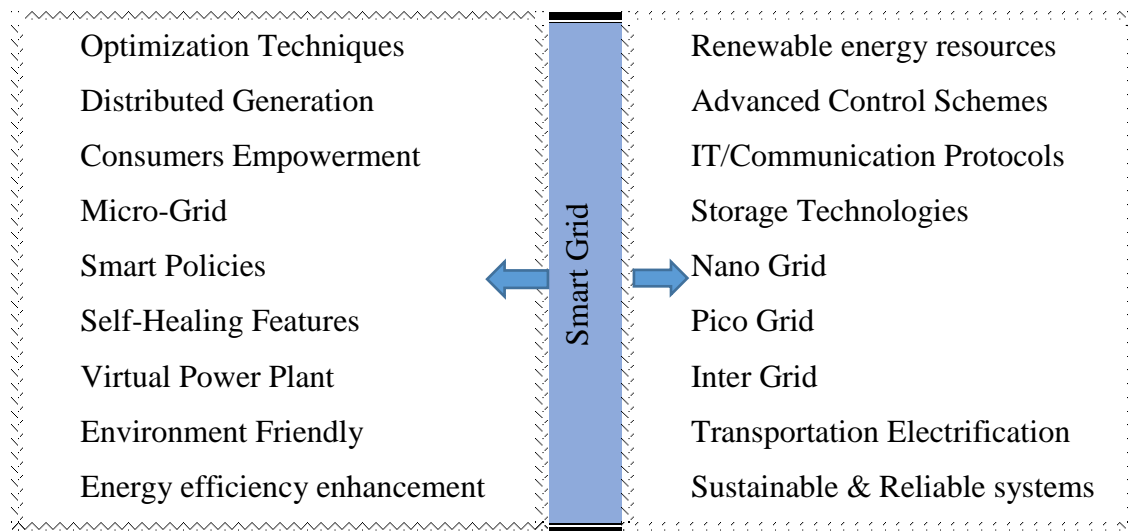
- i. allow generators of all sizes and technologies to connect and operate;
- ii. offer consumers the possibility to actively participate in the process that in optimize the operation of the system;
- iii. provide consumers with greater information and choice of supply;
- iv. reduce significantly the environmental impact of the whole electricity supply system; and
- v. improve the supply's reliability and security.

SG is different from the traditional grid in many ways as can be seen in Table 4-1. It is such a revolutionary power system that enables several possibilities around the components involved in the electrical grid to suit the current and future contexts. Table 4-2 depicts the general overview of the possibilities enabled.

Table 4-1: Comparison between traditional electrical grid and Smart Grid (Shaukat et al., 2018)

Traditional electric grid	Smart Grid
Electromechanical	Digital
One-way Communication	Two-way Communication
Centralized Power Generation	Distributed Power Generation
A small number of sensors	Full grid sensor layout
Manual monitoring	Automatic monitoring
Manual recovery	Automatic recovery
Failures and voltage outages	Adaptive and Islanded
Few user option	More user option
Hierarchical	Network
Blind	Self-Monitoring attribute
Manual check/test	Remote checks/test
Limited Control	Pervasive Control
Few Customer Choices	Many customer Choices

Table 4-2: Overview of possibilities with SG



The advantages of SG are many in comparison with TG. These advantages are advanced information technology usage, detecting easily losses and faults, and better manage the network just to name a few. In addition, many features characterized the SG. To mention a few of them, SG could be a self-healing grid, flexible to integrate decentralized renewable energy, interactive with consumers, enabling the improvement of power quality. More, the key technologies of the

SG are diverse. They comprise communications infrastructure, demand side management (DSM)/demand response (DR), advanced infrastructure metering (AIM), Sensing and control infrastructure, Renewable energy (RE), Energy storage (ES) and Electric vehicles (EV) integration capability, automation, etc. Advantages, characteristics and key technologies of the SG are presented in detail in Table 4-3.

4.3.3 Reasons for shifting from TG to SG

Many reasons motivate the necessity to transform the current grid and moving towards the SG.

Environmental reason: The share of fossil-fuel (ff) based energy production could be estimated at about 70% in 2022 (Wiatros et al., 2022). One of the consequences of that heavy dependence on ff sources is the high GHG emissions into the atmosphere. The induced global warming resulting from the greenhouse gas effects has caused the climate to change and the environment to degrade. Under a centralized configuration, remaining heavily dependent on fossil fuels could not help to satisfy the growing power demand and mitigate climate change. Decentralized energy resources (RE) are the only viable option, at the moment, and therefore the existing grid must be transformed to make decentralized forms possible (Sanches et al., 2011; Zareen et al., 2012).

Technical reason: The aging of the grid infrastructure and centralized electricity production may put the long-term power system in danger. Using electrical vehicles and smart appliances will likely cause the frequency of peak loads and power shortages to increase. In addition, managing a rapidly growing electricity demand would be an unrealistic task in the current context. Therefore, implementing advanced controlling devices and ICT in association with remote monitoring equipment and control of T&D substations could result in grid efficiency improvement.

Economic reason: The reliance on fossil fuels is being undermined by the economic crisis. For example, the Russia-Ukraine war that started in 2022 affected socioeconomic development resulting in inflation across the globe (Khudaykulova et al., 2022; Orhan, 2022). One of those consequences is the increasing price of fuel. Under such situation, authors (Sanches et al., 2011; Zareen et al., 2012) He suggested that fuel prices be reassessed to depend on energy imports and that investments in the grid for energy efficiency and power flow optimization could be profitable (maintaining of a reliable and high quality power supply).

Political reason: ECOWAS countries have agreed to collaborate through the creation of the West African Power Pool organization to build a strong power network across the region. They agreed also through the ECOWAS Centre for Renewable Energy and Energy Efficiency (ECREEE) to increase the share of RE in the energy mix by means of 1) grid-connected renewable energy and decentralized renewable energy solutions, 2) the implementation of energy efficiency measures, and 3) the target to reduce the distribution lines from the current levels of 15-40% to the World standard level below 10% (ECREEE, 2015b, 2015a)

Table 4-3: Advantages, characteristics and key technologies of the SG

Advantages of SG (M. R. Hossain et al., 2010; Li et al., 2011; Tenti et al., 2010; Zahedi, 2011)	Characteristics of the SG (Li et al., 2011; Wei, 2010; Zhou et al., 2010)		Key technologies of SG	
By using advanced information technology and smart appliances, energy efficiency is enhanced on the power grid, in businesses and homes	Self-Healing Grid	Two-way communication with local and remote devices helps to analyse the undesirable system conditions and act the ability of the grid for intelligent monitoring, diagnosis and reparation to result in the improvement of overall reliability, security, affordability, power quality and efficiency of the electrical network.	Communication's infrastructure	Can based on fibre-optics, power line carrier, and/or wireless radio networks to transfer massive amounts of data in SG and allow the real-time control of the grid to improve the system reliability, asset utilization, and security challenges
SG automates, monitors and controls the two-way flow of the electricity by means of advanced meters, sensors and digital controllers	Integrated Grid	An attribute that helps to enable a highly secure and efficient power supply delivering through the interregional power transaction, additional capacity and network redundancy with environment impact reduction	Demand side management (DSM)/Demand Response (DR)	Allow to maximize the end-use efficiency by means of energy conservation to avoid or post one the construction of new generation plants
Complex and real-time information about the grid performance can be gathered by transmission and distribution companies to improve control over the network	Cyber Security Enhanced Grid	An essential feature of the SG against malicious attack and disruption to improve recovery's speed of the system and to reduce the physical and cyber vulnerabilities.	Smart meter	Basic means of communication between the utilities and consumers that enables the consumers to monitor their consumption and communicate their real-time usage to the utilities

The improvement in detecting power lines losses and faults enhance the reliability of power supply	Interactive Grid with Consumers	A possibility that offsets new cost saving, energy efficiency products and attractive demand side management programs leading to the motivation of the end users to manage their energy consumption.	Renewable energy (RE), Energy storage (ES) and Electric vehicles (EV)	SG enables the integration of RE, facilitates energy storage system for back-up and electric vehicle's powering.
SG helps to reduce the transmission and distribution losses and to manage the voltage	Integration of Distributed Generation	To enable the accommodation of generations and storage systems resulting in a flourished market, exposure and mitigation of resources allocation inefficiencies.	Active Thermal Rating Monitoring (ATRM) (SCADA/EMS, flexibility and capability, instrument reliability)	To enhance the economical operation by providing mitigation in due time to avoid dangerous system insecurity conditions by tracking the thermal state of the equipment.
SG helps utilities to better manage their networks that can result in maintenance cost reduction	Improved Quality of Power	Improving power quality enables to balance the load sensitivity and consumers have the possibility to purchase the electricity at different prices with varying grades of power quality	Sensing and Control Infrastructures	Evaluate the stability and congestion of the grid, monitoring health of equipment, energy theft prevention, and support of control strategies
Possibility for consumers to better manage their energy cost and reduce the demand for electricity in peak times by using smart meters and appliances. Consumers change their electricity consumption based on the knowledge of their updated electricity usage during peak period to save money.	Resource Management with Asset Optimization	Operations optimization and increasing asset life are a SG's major objective (Efthymiou & Kalogridis, 2010; Zareen et al., 2012).	Phasor Measurement Units (High speed sensor)	When distributed throughout the grid, they help to monitor the power quality or respond automatically to them

Building more large power plants is reduced under SG implementation	Increased Visibility	Sensors infrastructure and communications network enable network operators to have better and greater observability into the grid's operational status	Outage Management and Active Fault Level Monitoring	Monitor the different location in the network in real time to assess the level of connected generation and overall fault level so that to ensure the security and quality of supply. This assessment is possible based on smart sensor with geographical information system (GIS).
Integration of RE is facilitated under SG and therefore decentralized energy production is much more promoted	Environmentally Friendly Network Operation	The reduction of carbon emission is mandatory	Flexibles AC Transmission Systems (FACTS) Devices	For a highly efficiency and reliable power grid with improved power quality and quantity through steady-state and dynamic reactive power compensation, voltage regulation; Steady-state and dynamic stability enhancement; increasing power transfer capability of existing
Enabling of Vehicles-to-Grid and Grid-to-Vehicles technology			Automation	assets; Reduced fault current; Reduced transmission losses; Improving power quality For rapid diagnosis of and precise solution to specific grid disruptions or outages
Favouring better environment			Advanced Analytic Application	Tools that managers and operators have to effectively and efficiently operate a grid with an increasing number of variables.

4.4 Methodology

This section describes the procedure utilized to achieve the findings of the current study. The study seeks to gain a comprehensive understanding of the power system in developing countries. The Togolese power system is investigated as a case study. Based on the findings of the latter study, a more resilient power system could be designed to address the issues the system faces. The methodology consisted of a thorough assessment of the Togolese power system in its different aspects, viz., generation, transmission, and distribution with numerous DRR. Again, the current investigation is based on an expert elicitation approach and a resilient power system, which is model-based oriented.

4.4.1 Thoroughly Assessment of Togolese power system

Expert elicitation uses expertise as a strategy to analyse a system or event. This approach is coupled with an active investigation. A thorough assessment of the Togolese power system was conducted based on the latter technique. The study investigated existing documents and reports produced by the Regulation Agency (ARSE), the international utility company (Benin and Togo) in charge of the transmission system (CEB), the national utility company (CEET), and the Rural Electrification and Renewable Energy Agency (AT2ER). Furthermore, an insightful discussion was conducted with energy specialists and employees from CEET, AT2ER, and the Ministry of Energy on the current situation of the power system. Various aspects were taken into account, as can be seen in Figure 4-2.

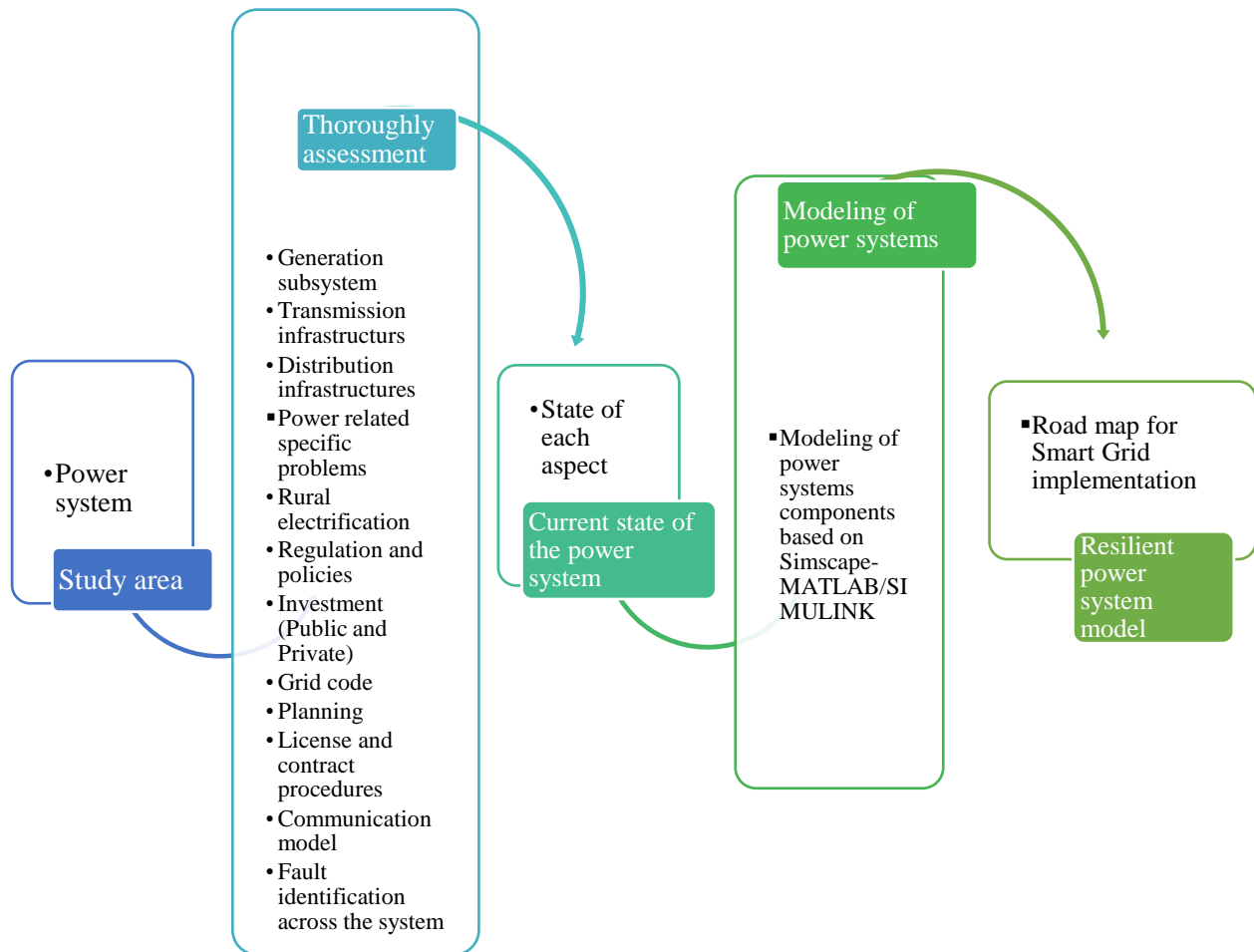


Figure 4-2: Diagram for expert assessment-modelling-based approach of power systems in Togo

4.4.2 Modelling of the power systems

Modelling of the Togolese power system was attempted in a view of transforming the system into a smart grid. A reliable and resilient power system constitutes the backbone of strong economic and sustainable development in both industrialized and emerging countries. Togo is no exception. Towards this perspective, the power systems are modelled given their transformation as a response to the plethora of difficulties encountered in the sector. In addition, a road map was proposed for the implementation of the smart grid. The modelling of the system evolves a number of components and procedures.

4.4.2.1 Simulation tool

The power system is modelled for better planning, expanding the system, and improving or transforming the system to meet the existing challenges. Operators use numerous of tools to

achieve their objectives. In the present study, Simscape-MATLAB/Simulink is used to model the Togolese power system because it allows the modelling of a power system with integration of renewable energy resources.

4.4.2.2 Power system components modelling

4.4.2.2.1 Thermal plant

Fig 4-3 presents the functional structure of thermal power plant. Different components encountered are:

- ❖ a diesel engine is modelled by a transfer function of the first order (Bagre et al., 2013; Stavrakakis & Kariniotakis, 1995). It gives the relationship between fuel consumption and mechanical power supplied.

$$\begin{cases} P_m = A \dot{m}_b - B(\omega_b)^2 \\ \dot{m}_b = \exp(-p\tau) m_b \end{cases}$$

Where,

P_m is the mechanical power generated by the diesel engine.

\dot{m}_b is the actual Fuel flow in (kg/s).

A is the power gain in (puW.s/kg)

B is the mechanical power losses in ((pu)W/(pu)rad/s).

ω_b is the mechanical speed of the engine ((pu) rad/s)

τ is engine time delay (s) The constants.

A and B are determined by estimating the fuel consumption as linearly dependent on power supplied.

$A = 153.85$ puW.s/kg and $B = 0.0769$ (pu)W/(pu)rad/s in this study their value. In the combustion chamber, the time-delay τ of the fuel self-ignition is taken steady (Claeys, 2011) and equal to 0.024s. The speed controller used is a proportional integral (PI) (Hazel, 2000) because it avoids a static error in steady state (Claeys, 2011; Hazel, 2000; Stavrakakis & Kariniotakis, 1995).

- ❖ a synchronous generator. The dynamic model of this synchronous machine is based on the classical Park's transformation. The model used is developed in MATLAB Simulink Power Block Set (Bagre et al., 2013). The excitation system is adopted from Powerlid MATLAB/Simulink libraries. It is a standard model of IEEE "Excitation type 1" (Bagre et al., 2013; Stavrakakis & Kariniotakis, 1995). Its block diagram is shown in Fig.4-4.

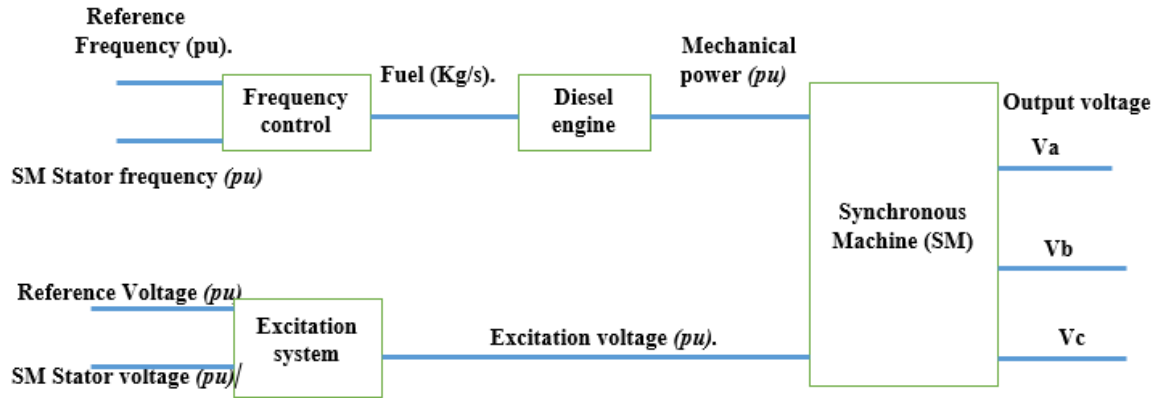


Figure 4-3:Functional structure of a thermal plant (Bagre et al., 2013)

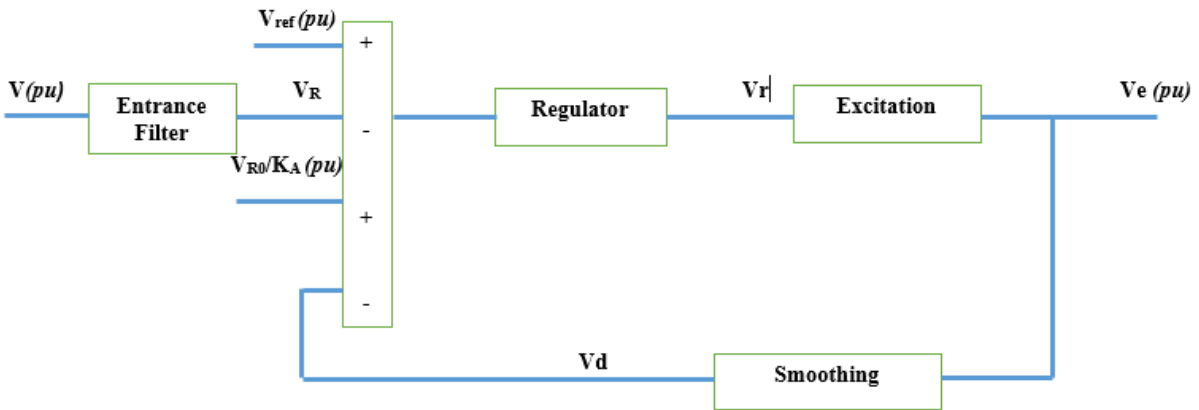


Figure 4-4:Block diagram of the generator excitation system (Bagre et al., 2013)

4.4.2.2.2 Solar plant model

The functional structure of a solar plant is simplified in Fig.4-5. The energy harvested, from solar is produced by means of solar cells assembled to form a panel. This technology transforms sunlight into electricity through the photoelectric effect. DC current and voltage are produced. An inverter then transforms the DC parameters into alternative current (AC) to either power AC appliances or to be integrated into the grid.

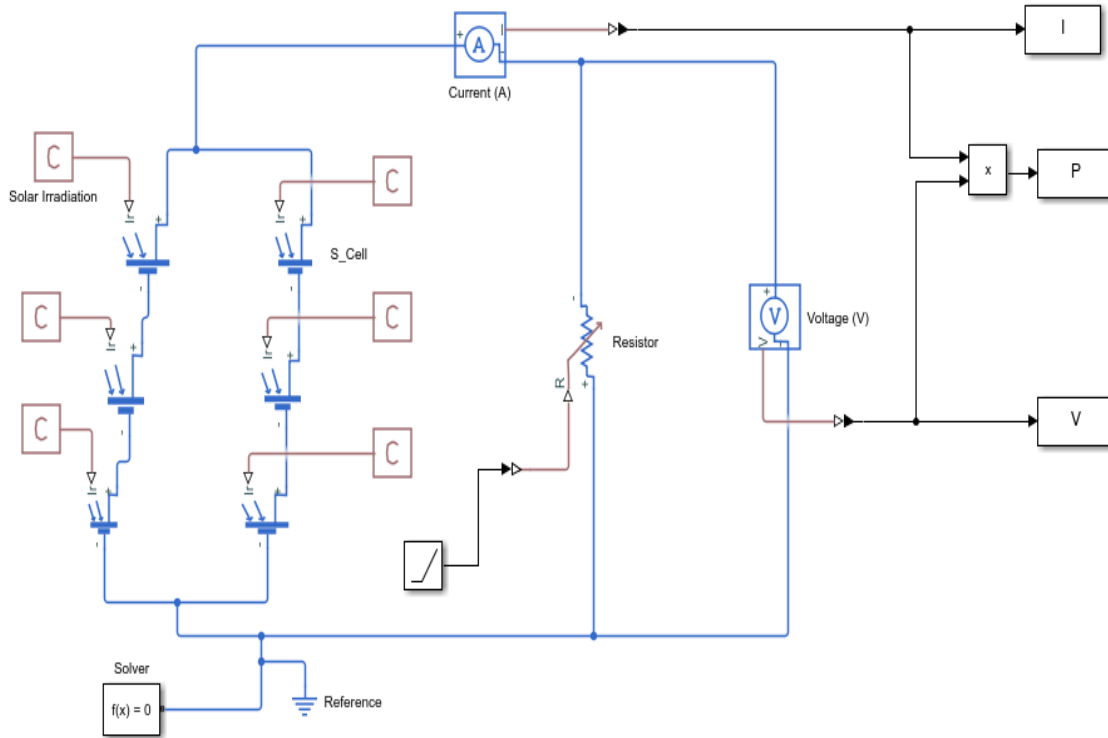


Figure 4-5: Functional model of photovoltaic effect

4.4.2.2.3 Design of boost converter

The booster converter is designed based on the parameters presented in Table 4-4 and equations (4-1) to (4-5).

Table 4-4: Boost converter parameters

Parameters	Values
Maximum power point voltage (V _{mpp})	1233V
Reference voltage for the bus (V _{bus_ref})	1500V
Input voltage of boost converter (V _{in})	1233V
Output voltage of boost converter (V _o)	1500V
Switching frequency of boost converter (f _{sw_boost})	10000Hz
PV rated power (P)	50 MW

$$D = 1 - \left(\frac{V_{in}}{V_o}\right) \quad (4-1)$$

$$L_{bound} = (1 - D)^2 * D * (V_o^2) / (2 * f_{sw_{bosst}} * P) \quad (4-2)$$

$$L_{boost} = 10 * L_{bound} \quad (4-3)$$

$$C_{boost_min} = (D * P)/(0.01 * Vo^2 * fsw_boost) \quad (4-4)$$

$$C_{boost} = 1000e - 6 \quad (4-5)$$

4.4.2.2.4 Design of the filter

The filter is designed based on the parameters presented in Table, and equations (4-6) and (4-7).

Table 4-5:Filter parameters

Parameters	Values
Sampling time (Ts)	1e-6 second
Rated power (P)	50MWp
Inverter phase2phase voltage (U)	161000V
Grid frequency (f)	50Hz

$$Lf = ((0.1 * U^2)/(2 * pi * f * (P/3))) \quad (4-6)$$

$$Cfmax = (0.05 * P)/(2 * pi * f * U^2) \quad (4-7)$$

4.4.2.2.5 Maximum power point tracker (MPPT) algorithm

The performance of PV systems is affected by local conditions. The extraction of maximum power from these systems is closely dependent on irradiation, load profile, and temperature. Solar modules produce maximum power at a point of the I-V characteristic where current and voltage are at their highest. It is known as the maximum power point (MPP). The maximum power point tracker (MPPT) algorithm can make a solar module generate maximum power (Saravanan & Ramesh Babu, 2016). A lot of such algorithms have been developed and the Perturb and Observe (P & O) method was used in this study. This algorithm is good because of its simplicity and can be implemented easily. MPPT algorithm is necessary in PV application to harvest the maximum power under varying weather conditions.

The P&O method compares the PV output power with the previous PV output power by periodically sensing the panel operating voltage. The variation in power (ΔPPV) is measured. If ΔPPV is positive, the perturbation of the operating voltage and the increment need to be the equal course. Nevertheless, if ΔPPV is negative, the system operating point obtained moves away from the MPPT and the operating voltage must be in the opposite direction of the increment (Bhatnagar & Nema, 2013), perturbation should be reversed to move back towards the MPP. Regardless of the irradiance and PV module's terminal voltage, this process continues until Eq. (4-8) is satisfied.

$$dP_{pv}/dV_{pv} = 0 \quad (4-8)$$

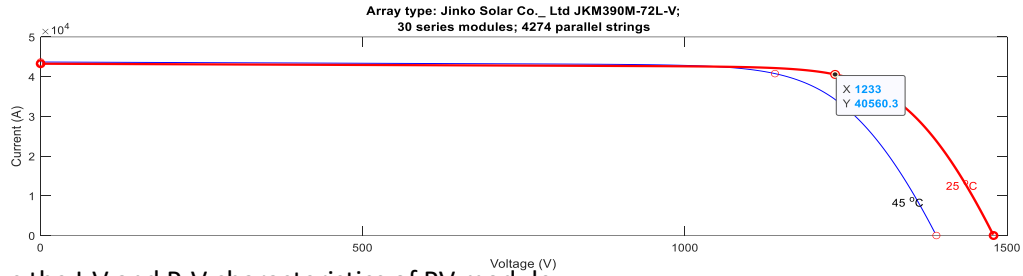


Fig. 4.6 shows the I-V and P-V characteristics of PV module.

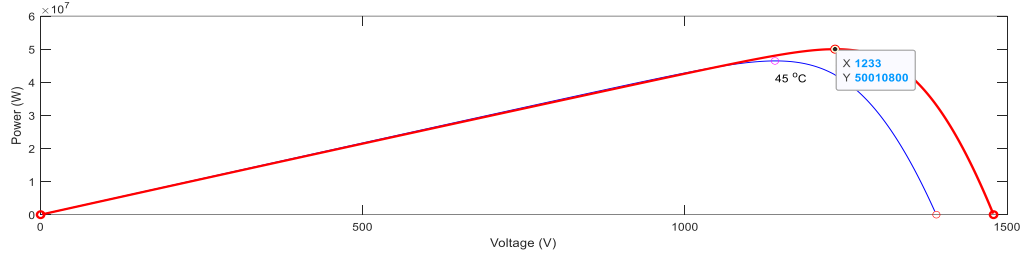


Figure 4-6: V-I and P-V characteristics

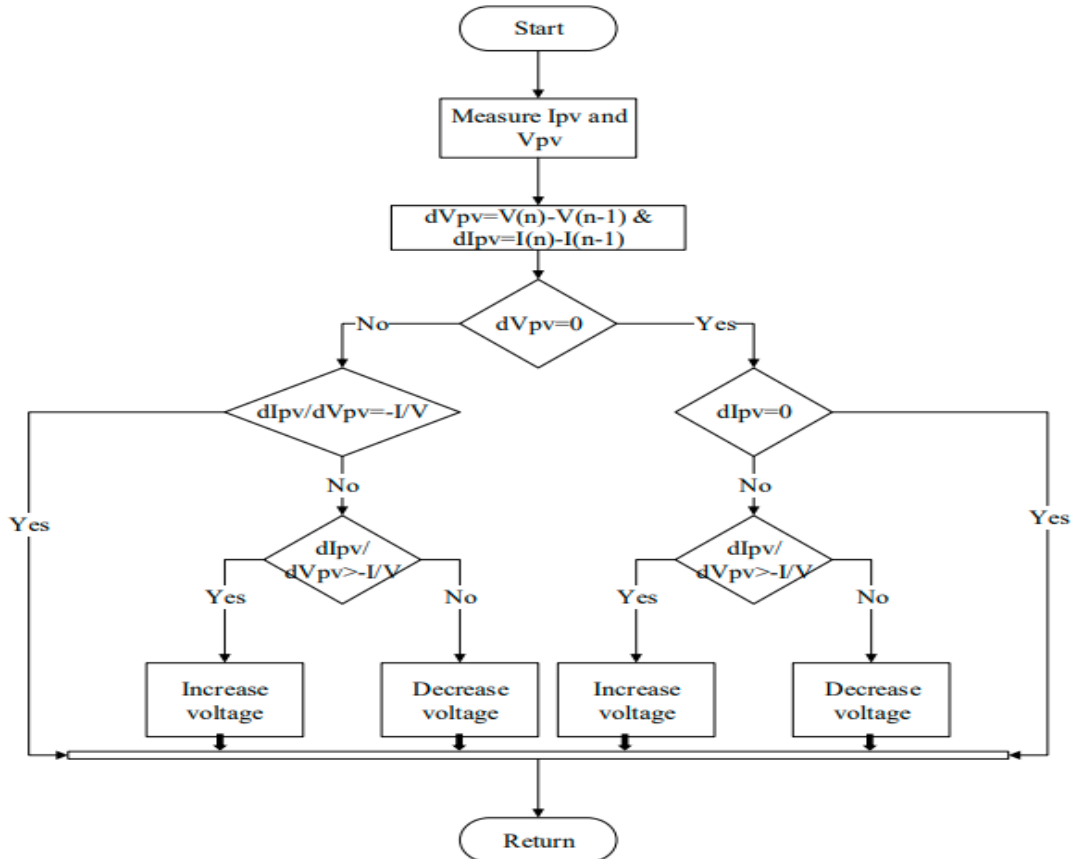


Figure 4-7: Flowchart of P&O algorithm adapted from (Bhatnagar & Nema, 2013)

4.4.2.2.6 Transformer model

The three (3) phases transformer of Simscape in the specialized power system block with two windings has been used. The transformer's windings can be connected in Y, Y with accessible neutral, Grounded Y, Delta (D1) or in Delta (D11). Delta lags or leads Y by 30 degrees or Delta (D11). All the transformers are Y/grounded Y in the study.

4.4.2.2.7 Transmission and distribution line model

In this study, power lines are modelled with three phase distributed parameters lines blocks. The following parameters were provided:

- i. Number of phases,
- ii. Length of the line (Km),
- iii. Frequency (Hz),
- iv. Resistance per unit length (Ω/km), $[r, r0]$,
- v. Inductances per unit length (H/km), $[L, L0]$. The value of zero-sequence inductance is different from zero because it would end result in an invalid propagation velocity computation, and
- vi. Capacitances per unit length (F/km), $[c1, c0c]$. The value of zero-sequence capacitance is also different from zero because it would end result in an invalid propagation speed computation (Mathworks, 2018).

4.4.2.2.8 Load model

The load is modelled by three phase load blocks of the specialized power system blocks under Simscape. The parameters of the load block include 1) configuration (Y, D), 2) nominal phase to phase voltage, 3) nominal frequency, 4) active power, 5) inductive reactive power, and 6) capacitive active power.

4.4.2.3 Togolese power system modelling

Power system modelling has been always a challenging task because of its complexity due to the strong interactions between a large number of distributed components (Bagre et al., 2014). Regardless the type of grid, the quality of supply voltage, the safety and reliability of the grid have to be assured throughout the overall power system (P. Kundur, 1965). The Togolese national grid

has been then modelled step-by-step based on Simscape-MATLAB/Simulink tool following these modelling principles:

- i. Modelling all components (generators, transformers, capacitor, loads, cable, circuit breakers etc...) related to a specific power plant or substation,
- ii. link each component to others for the whole power plant or the substation to form one entity, such as the CGT power plant station in Figure 4.7,
- iii. then link all the power plants and substation together according to the region layout to form the Regional Network, as the Central Region Network shown in Figure 5.
- iv. finally interconnect all the regional networks and imported sources to form the Togolese interconnected network (TIN).

4.4.2.4 Assumptions of the Simulation in the steady state

The modelling of the TIN grid (lines, power plant data, distribution of loads, etc.) is based on data collected from ARSE reports and the CEET. In addition, we added some assumptions to bridge the missing information at the time of the study. To solve both the complexity and the range of validity of the model, many simplifying assumptions have been made for the simulation as in (Bagre et al., 2014; Bastard, 1998). The principal assumptions are:

- The steady state's behaviour is studied at 50 Hz,
- The network is linear, and
- The power system is perfectly balanced.

4.4.2.5 Test of power plants models

The power plants are modelled and simulated as 1) standalone for thermal systems and 2) grid connected for solar system. Their respective installed capacities were then incrementally obtained. Figures 4.7 to 4.16 present the plants and their outputs.

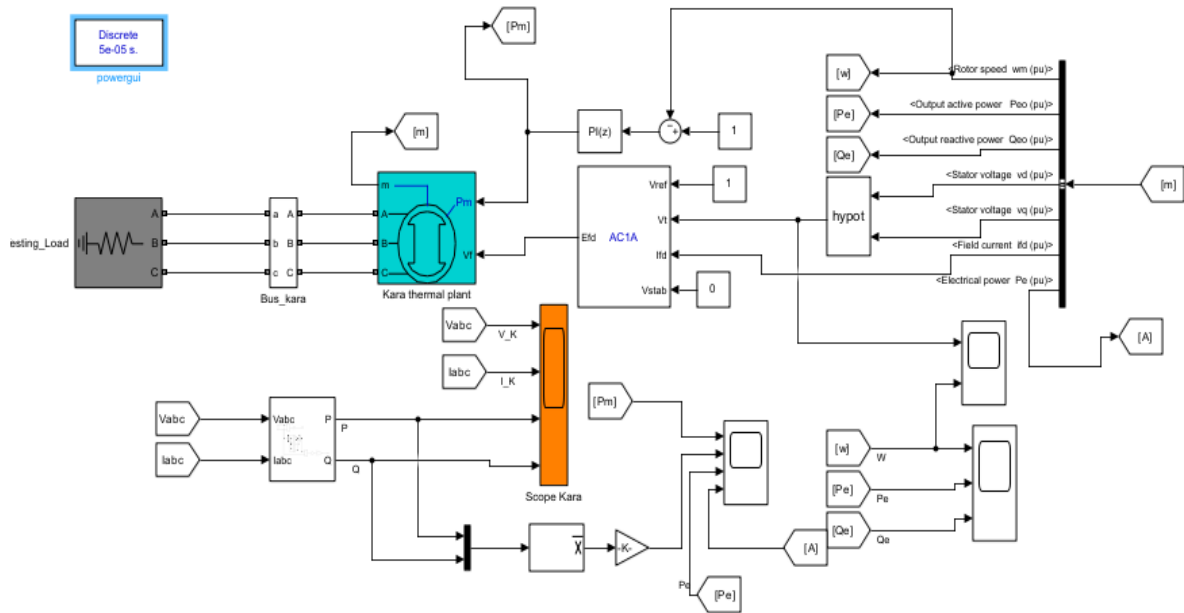


Figure 4-10: Kara thermal plant

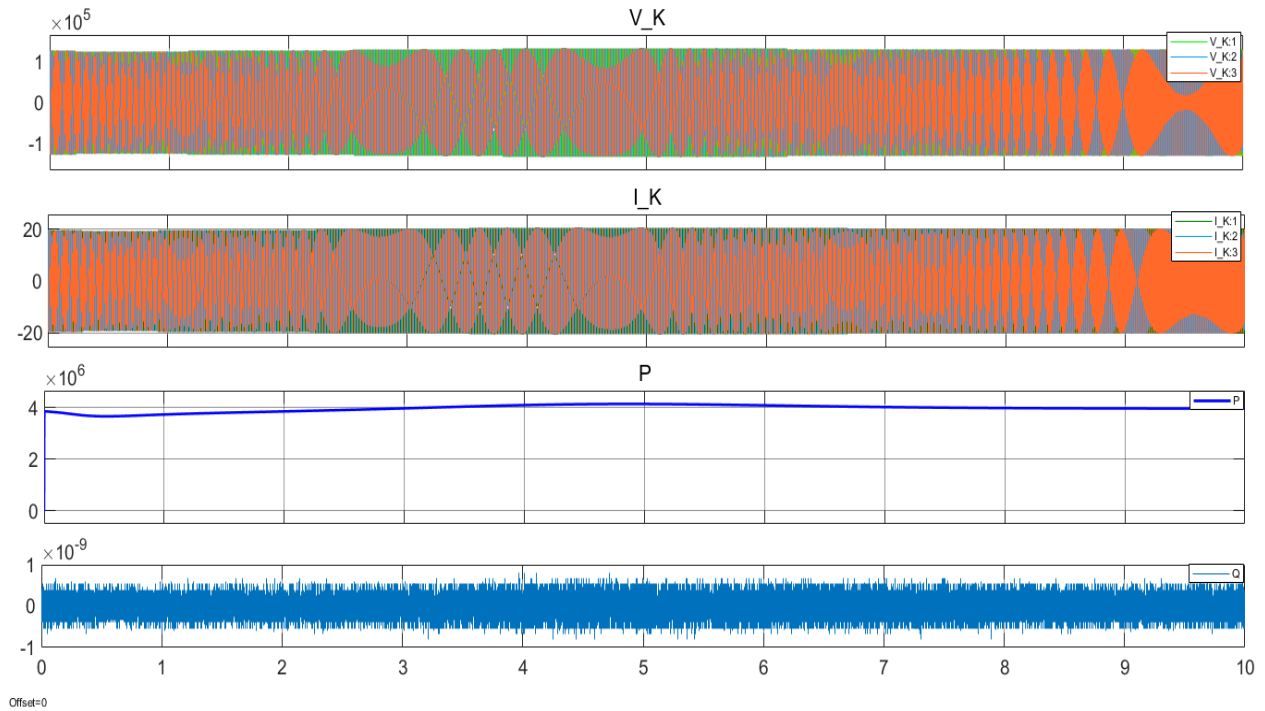


Figure 4-11: Kara thermal plant outputs vs time (s)

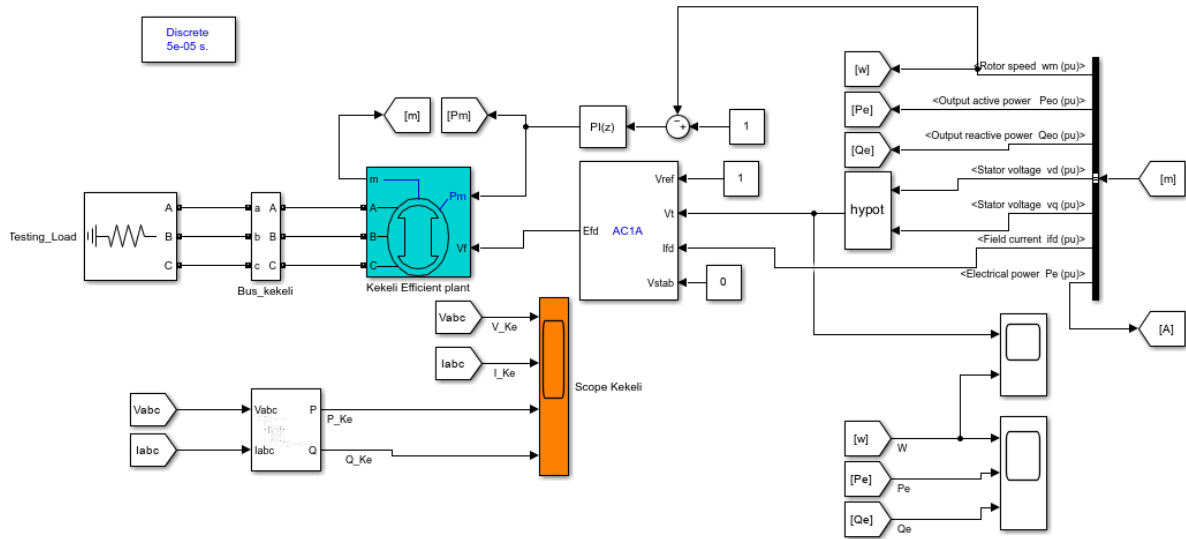


Figure 4-12: KEKELI Efficient thermal plant

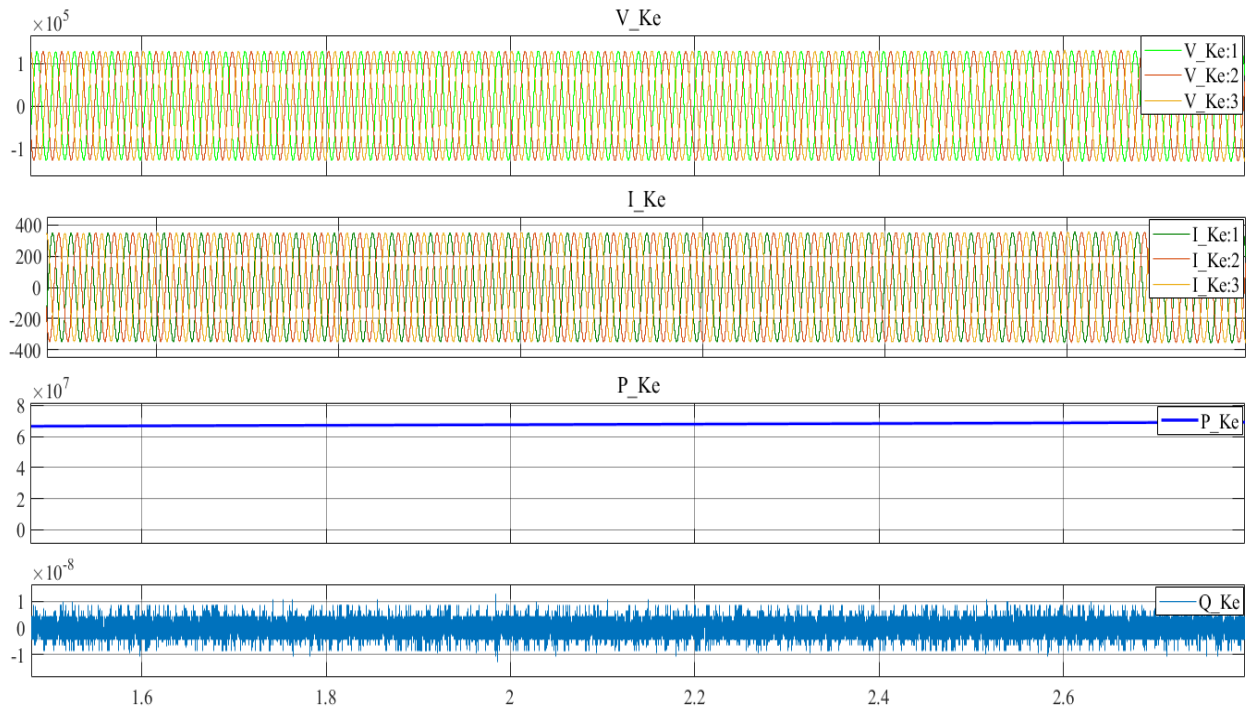


Figure 4-13: KEKELI Efficient thermal plant outputs vs time (s)

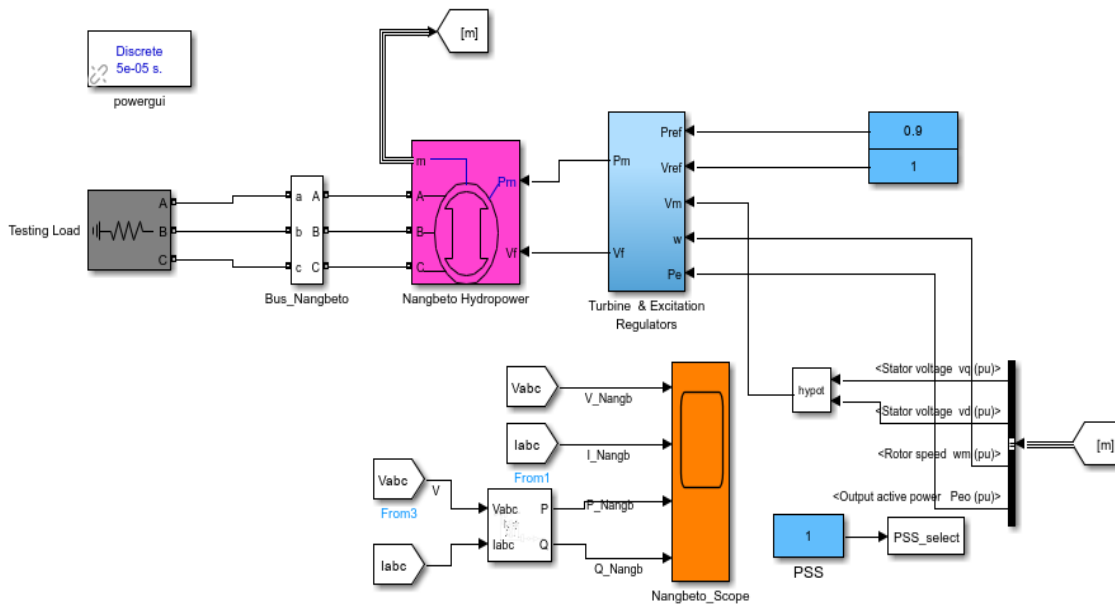


Figure 4-14: Nangbeto Hydropower

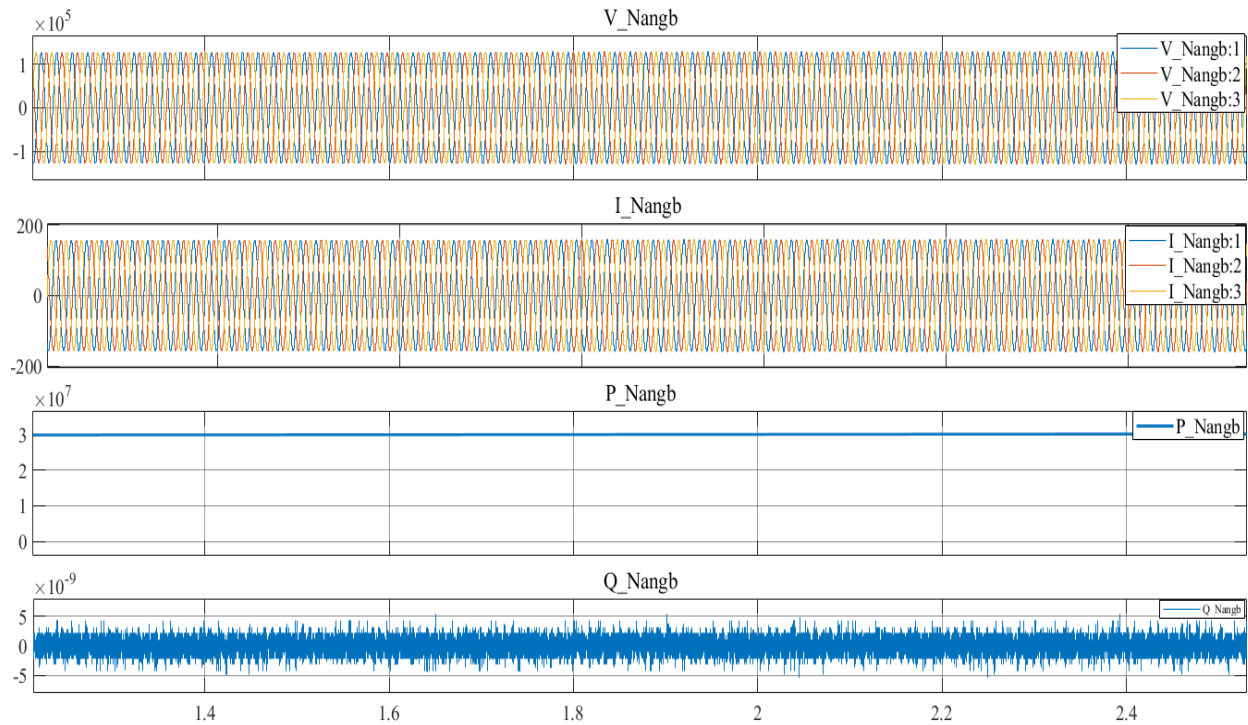


Figure 4-15: Nangbeto Hydropower outputs vs time (s)

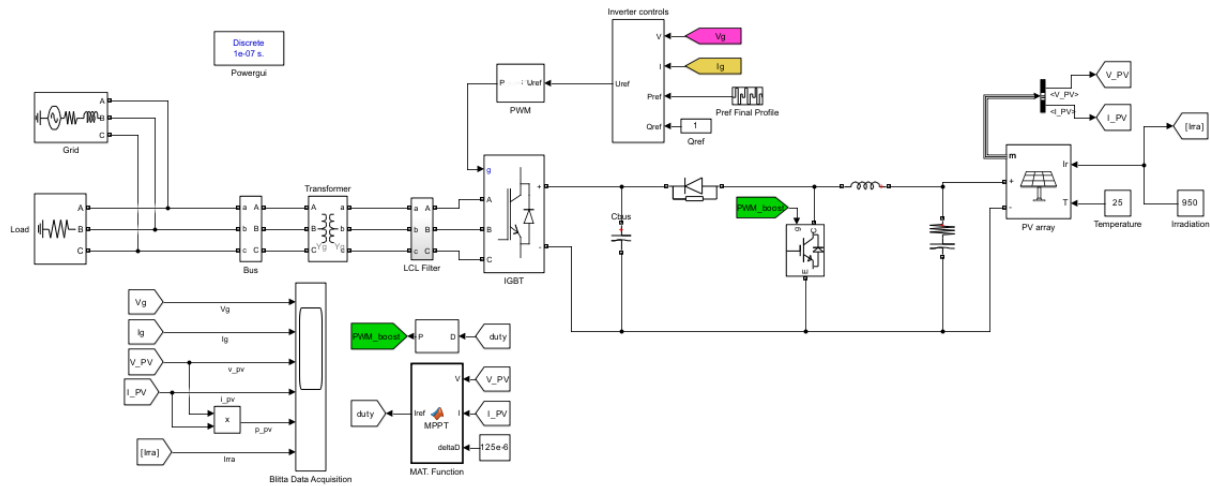


Figure 4-16: AMEA Solar plant Grid-connected

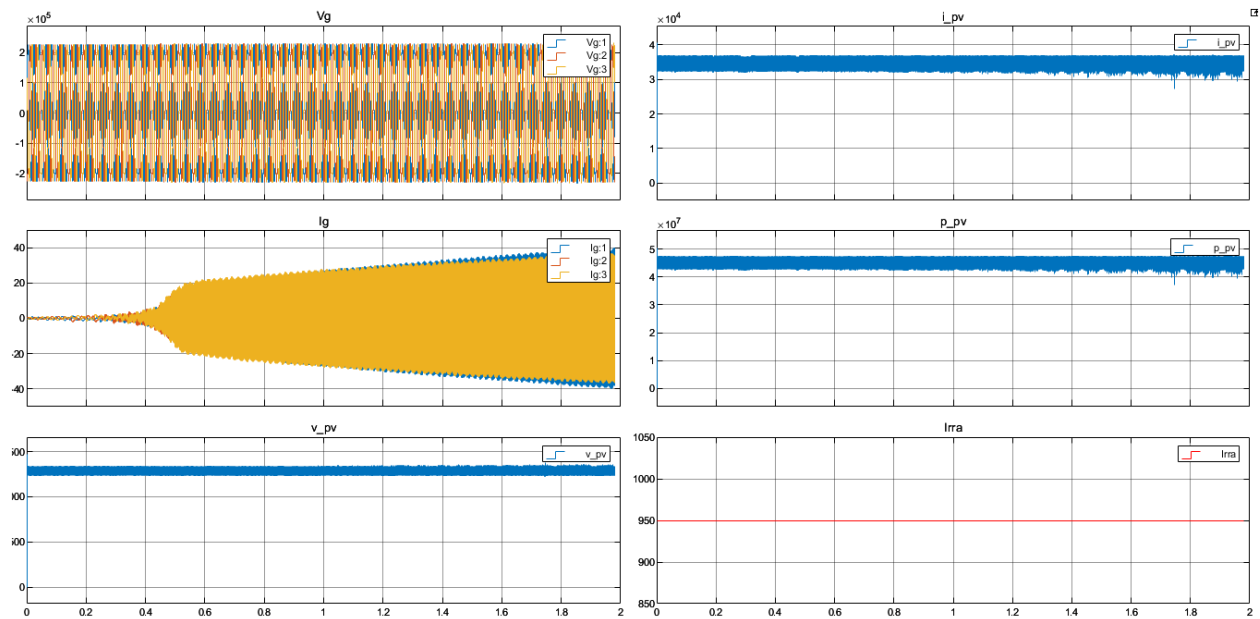


Figure 4-17: AMEA Solar plant outputs vs time (s)

4.5 Results and discussion

4.5.1 Status of the Togolese power system

The Togolese power system has been assessed. The assessment has resulted in an analysis of the different aspects of the system.

4.5.1.1 Power Generation

In Togo, power is produced by hydropower, thermal plants, and solar energy. Their installed capacities are 34.1 MW, 160 MW, and 6.46 MW, respectively. At the time of this study, 65 MW

of thermal and 70 MW of solar were under construction. The existing electricity facilities are owned by three major utility companies: 1) the international utility company CEB responsible for the transmission, 2) the national utility company CEET responsible for the distribution, and 3) the independent power producer (IPP). Table 4-6 presents the installed power capacities.

Table 4-6: Installed power capacities.

<i>Companies</i>	<i>Regions</i>	<i>Localities</i>	<i>Capacity (MW)</i>	<i>Types</i>	<i>Status</i>
<i>CEET</i>	Maritime		2*0.800		Operation
			3*1.000		
		Lomé	0.504		
			11*0.985		
		Kpekplémé	0.176		
		Ahassome	0.08	Thermal	
		Tado	0.2488		
		Saligbé	0.08		
		Mamakopé	0.04		
		Badou	0.352		
		Plateaux	Kpimé	1.6	
		Bavou	0.15	Solar	
		Djon	0.1192		
		Yegue	0.0528		
		Sokode	0.1	Thermal	
	Central	Djarkpanga	0.1192		
		Tandjassi	0.1		
		Assoukoko	0.25	Solar	
			1.6		
			1		
		Kara	1.28	Thermal	
			0.8		
	Kara	Bandjeli	0.1		

		Dimori	0.1		
		Koutoum	0.1	Solar	
		Fare	0.036		
		Mandouri	0.352	Thermal	
	Savannah	Dapaong	2*0.985		
		Takpiéni	0.1	Solar	
<i>CEB</i>	Plateaux	Nangbeto	32.5	Hydro	
		Tag Togo	20	Thermal	
<i>CGT</i>		Lomé	100	Thermal	
<i>KEKELI Efficient Plant S.A.</i>	Maritime	Lomé	65		Construction
<i>AMEA Solar Plant S.A.</i>	Central	Blitta	70	Solar	Construction
<i>Importation</i>			360.02		

4.5.1.2 Power supply and demand

Togo lacks enough energy to meet its growing electricity demand as access to electricity is still limited (Amega et al., 2022). Notably, figure 4-18 depicts regional electricity access rates. It can be seen how power is unevenly distributed across regions. Current power consumption is much more dependent on economic activities and income than it is on population. Thus, Lomé, the capital city of Togo, takes the lead in power demand because it is the most developed region with numerous economic activities. Add to this, figure 4-19 presents the shares of national electricity demand by economic sectors. Industry leads in power demand followed by the residential sector. Power supply and demand are closely linked. In 2020, supply could not balance demand because power production was not growing as fast. Table 4-6 shows the available supply capacity across the country, as well as the corresponding companies and sources.

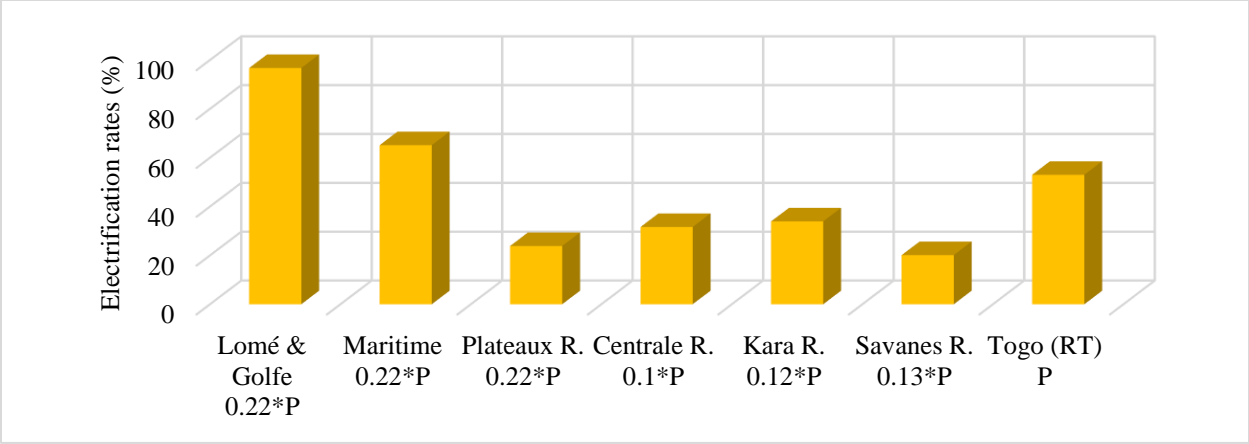


Figure 4-18: Electricity access rate at regional and national levels in 2020 (ARSE, 2020b)

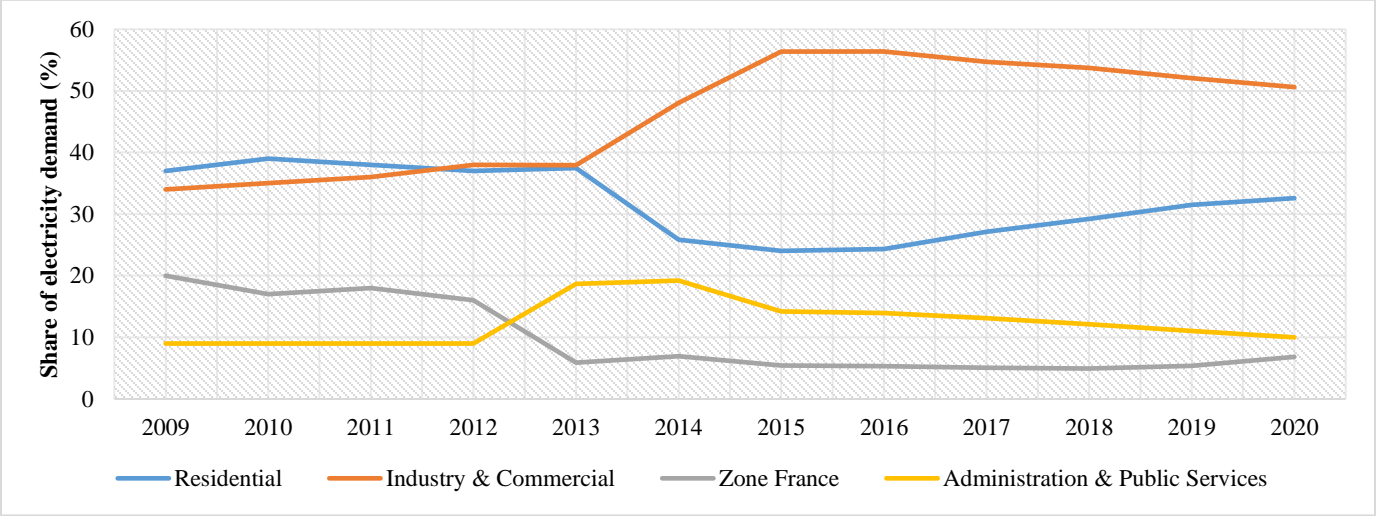


Figure 4-19: Share of power demand by sectors, Togo

4.5.1.3 Transmission and distribution infrastructures.

This section presents CEB’s transmission and CEET’s distribution lines. The system is an alternative current (AC) with a frequency of 50 Hz. Distribution lines are divided into urban, suburban, and rural lines. The distribution system typically consists of medium and low voltages, such as 34.4KV, 33KV, 20KV, 5.5KV, and 0.4KV (ARSE, 2020b). Transformers at the distribution level step down the lines' voltage to 400V and 220V for industrial and residential consumers, respectively. Until 2020, the distribution infrastructure was still limited, even in the largest cities, where there were vast informal lines from grid-connected homes to many neighbourhoods. Many issues were encountered in this subsector, such as line losses depicted in Figure 4-20. This situation is a call for the need to enhance the efficiency of the subsystem. Conversely, the transmission subsystem consists primarily of high voltage infrastructures. This

power subset is composed of line voltages of 61KV, 66KV, and 34.5KV. In addition, the Togolese high voltage lines terminate at 161KV/11KV, 161KV/20KV, 161KV/22KV, 161KV/34.4KV, 161KV/63KV, and 161KV/66KV stations. The transmission and the distribution lines are presented in Table 4-7 and 4-8.

Table 4-7: Transmission infrastructure of CEB in 2022 (CEB, 2022)

Adm. Regions	Lines	No.	Voltage (KV)	L. (Km)	Transformers stations		
					Types	Capacity (MVA)	No.
Voltage 161 KV							
Plateau	Nangbeto-Atakpame	1	161	36.5	(161KV/20KV; 16) (20KV/34.5KV; 5)	2	
Plateau - Maritime	Nangbeto-Mome Hagou	1	161	216	(161KV/63KV; 50)	3	
Plateau- Central	Atakpame-Sokode	1	161	184.42	(161KV/66KV; 50) (161KV/20KV; 20)	2+2	
Central- Kara	Sokode-Kara	1	161	61.76	(161KV/20KV; 16) (161KV/34.5KV; 7) (161KV/22KV; 16)	1+2 +1	
Maritime	Lomé Aflao-Davié	2	161	38.3	(161KV/20KV; 50)	3	
	Davié-Legbassito	2	161	14	(161KV/20KV; 50)	2	
	Lomé Aflao-Lomé Port	2	161	17	(161KV/20KV; 35) (161KV/20KV; 25) (161KV/11KV; 35)	2+1 +1	
Voltage 63 KV							
Central- Kara	Kara-Sokode	1	63	76			
Maritime	Mome Hagou- Anfoin	1	63	20			
	Mome Hagou- Tabligbo	1	63	9.35			

Savannah	Mome Hagou-SNPT	1	63	24		
	Voltage 34.5KV					
	Bawku-Dapaong	1	34.5	36	(34.5KV/22KV; 5)	1+1
					(34.5KV/22KV; 2)	

Table 4-8: Distribution infrastructures of CEET in 2020 (ARSE, 2020b)

Distribution infrastructure (DI)

Regions (Urbans)	Type de lines	L(km)	Other specifications	
Maritime	33KV	144	Transformer Station MV/LV	5.5KV/0.4KV
	20KV	118.7		20KV/0.4
Plateaux	33KV	238		33KV/0.4KV
	20KV	40		34.5KV/0.4KV
Central	33KV	104	Interurban MV distribution lines	34.5KV
	20KV	59		33KV
Kara	33KV	75		20KV
	20KV	72.662		5.5KV
Savanah	20KV	30.068	Urban & rural MV & LV distribution lines	20KV & 0.4KV



Figure 4-20: Distribution lines losses

4.5.1.4 Detailed assessment of the Togolese power system

4.5.1.4.1 Assessment of components of the system

In this section, the key components of the power system were identified and analysed in a tabular fashion. As can be observed in Table 4-9, the fundamental picture of the country's electricity system is described and highlighted.

Table 4-9:Togolese power system components-based assessment

Aspects under consideration	Generation	Transmission	Distribution	Off-Grid
Energy Strategy	Developed as in Togolese Electrification Strategy	Developed as in Togolese Electrification Strategy and may be improved	Developed as in Togolese Electrification Strategy and may be improved	Developed as in Togolese Electrification Strategy and may be improved
System Planning	Developed as in Togolese Electrification Strategy	Stated as policy in the Togolese Electrification Strategy and may be improved	Developed as in Togolese Electrification Strategy and may be improved	As planned in the Togolese Electrification Strategy and may be improved
Power Sector Governance	Governed by the International agreement on the revised Benin-Togolese electricity code (2003), Law n° 2000-012 of July 18, 2000 on the electricity sector and Law n°2018-010 on the	Exist as in the International agreement on the revised Benin-Togolese electricity code of 23 December 2003	Exist as in Law n° 2000-012 of July 18, 2000 on the electricity sector	Law n°2018-010 on the promotion of electricity production from renewable energy sources in Togo and establish of Rural Electrification and Renewable

	promotion of electricity production from renewable energy sources in Togo and Regulation Agency (ARSE)			Energy Agency (AT2ER)
Power Sector Framework	Exist under State Monopoly	Under the responsibility of CEB	Under the responsibility of CEET	Under the responsibility of AT2ER
Private Sector Participation Models	Independent Power Producer (IPP)	Not exist by now	Not exist by now	Yes, but may be greatly improved
Procurement Process	Exist and regulated by ARSE under the supervision of the Ministry of Energy	Not exist by now	Not really	Possible
Contracts Regulation	Contracts regulated by ARSE under the supervision of the Ministry of Energy	Yes	Not exist by now	Very possible but the process is tight
Economic Regulation	Unknown	Yes	Yes, and may be improved	Possible but may be improved
Credit Enhancement	Exist and can be upgraded (Unknown)	Unknown	Unknown	Unknown
Authorizations and Permits	Possible and regulated by ARSE	At this moment, Only CEB is responsible for	At this moment, Only CEET is	Possible under regular process

			the transmission sector (HV)	responsible for the distribution sector (MV & LV)	
Grid Code	Exist and can be upgraded	Yes		Exists in form of Distribution Technical Regulation	Not exist
Grid Access	Exist but can be revised to meet smart grid standards	Yes, and may be improved		At infancy stage	Might be possible
System Quality and Security Standards	Developed	Yes, and may be improved		Yes, and may be improved (under development)	AT infancy stage and may be improved
Access to Data	May be possible upon request	Possible upon request		Might be possible upon request but the tight process	Might be possible upon request
Power Sector Competition	Under development (Regional Electricity Market)	Not exist		Not exist	Opened but tight

Generation Options	Off-taking	Possible under agreement	NA	NA	NA
Incentives		Taxes reduction regarding RE equipment importation	Unknown	Unknown	Unknown
Indirect Incentives		Unknown	Unknown	Unknown	Taxes reduction on equipment importation
Off-grid System Integration		NA	NA	NA	Possible but need to be extended and improved
Investment		The effort is being made but still limited	The effort is being made but still limited	The effort is being made but still limited	An effort is being done but still limited
Related problems		Limited production to meet the increasing demand	Aging of the infrastructure, faults & losses	Aging of the infrastructure, faults & losses, tariff adjustment very difficult	Unknown

4.5.1.4.2 Communication and metering schemes

The traditional means of communication between power operators and consumers (telephone, email, visits) remain in use. The power systems sector is neither digitalized nor is it in the process of being digitalized. However, the metering system implemented may prove to be an invaluable step toward modernization. Thus, there are two types of electricity meters. The traditional measurement system in which a CEET technician has to regularly return to the client's premises to record their consumption. The second option is a prepaid electricity metering system. The following are general methods of communicating with the distribution system:

- Technicians at the dispatching stations record the consumption per hour (kWh) and communicate the values to the Central Control Office. Note: A SCADA project is underway and should be operational by 2024.
- The two end points, i.e., station and end-user, have the technology to communicate remotely. But there is no supervisory system installed yet. Thus, remote management cannot be done at the moment.

In the event of a fault, the breaker at MV station opens automatically. The faulty section is not automatically detected. A trial and error search are carried out to identify the section. Installation of communicating fault detectors would allow for automatic detection, thereby saving time and labour costs.

4.5.2 Simscape model of the Togolese interconnected network (TIN) developed

The national network interconnected can be divided into 5 sub-networks including Maritime, Plateau, Central, Kara and Savannah sub-directorates. The electricity imported from Ghana is sent to Togo through the links Akosombo, Davie and Dapaong power substations located in the Golf, Maritime and Savannah regions. The electricity imported from Nigeria is sent to Togo through the link Mome Hagou substation via Benin. The models of the 5 directories are Maritime, Plateaux, Central, Kara and Savanes directories.

- Maritime directory encompasses substations like Lomé AFLAO, Lomé Port, Legbassito and Davié and Mome Hagou (Figure 4-21).
- Plateau directory is composed of Atakpame substation that supplies Ogou, Notse, Agbelouve, Kpalime, Adeta, Agou, etc (Figure 4-22).
- Central directory is composed of Sokode substation that supplies Sokode, Sotouboua, Blitta, Tchamba, Kamboli, etc. (Figure 4-23).

- Kara directory is composed of Kara substation that supplies Kara city, Kante, Pagouda, Bassar cities etc. (Figure 4-24).
- Savanes directory is composed of Dapaong, Cinkasse and Barkouassi substations (Figure 4-25). They supply Cinkasse, Dapaong, mango and other cities of the region.
- All the regional power systems and imported power from the neighbouring countries were connected to form the Togolese interconnected network (NNI) as depicted in Figure 4-26.

Within the country are isolated mini-grids powered either by thermal or solar energy and an isolated interconnection point with Ghana that supplies Badou, Akebou, etc.

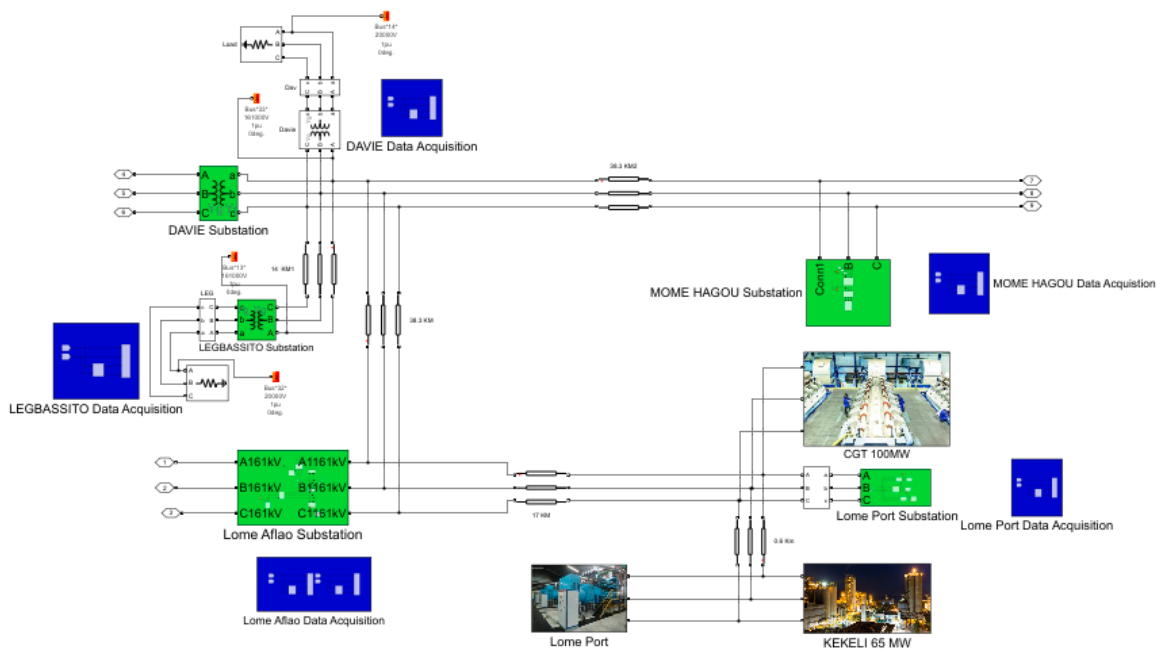


Figure 4-21: Simscape of Maritime power system

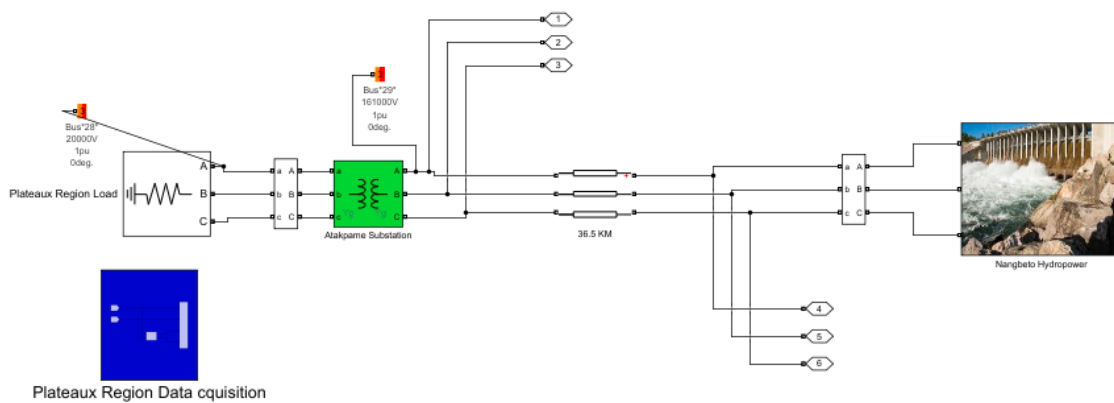


Figure 4-22: Simscape of Plateaux power system

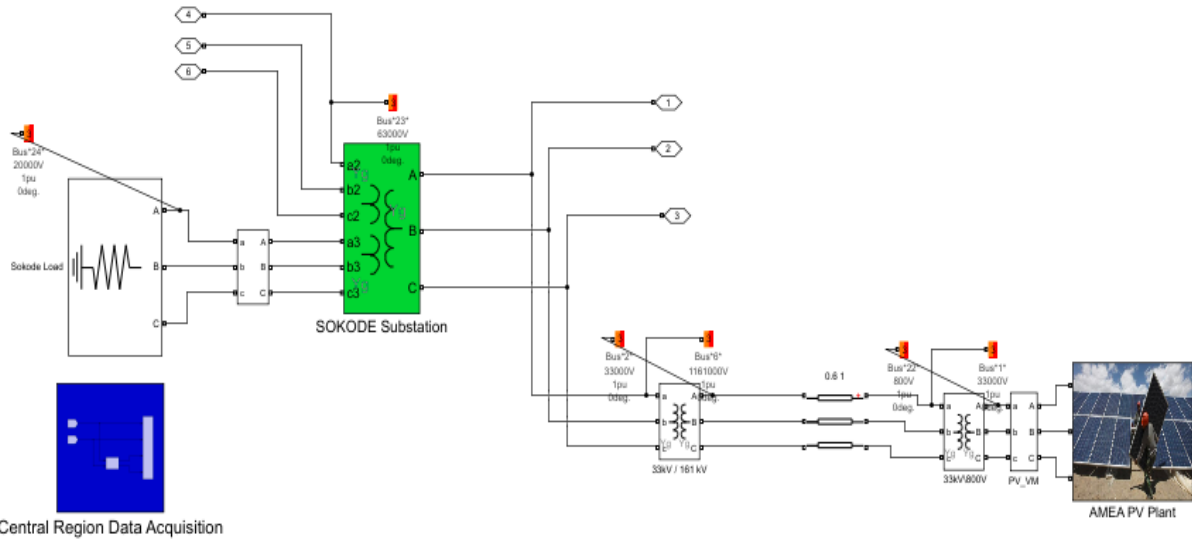


Figure 4-23: Simscape of Central region power system

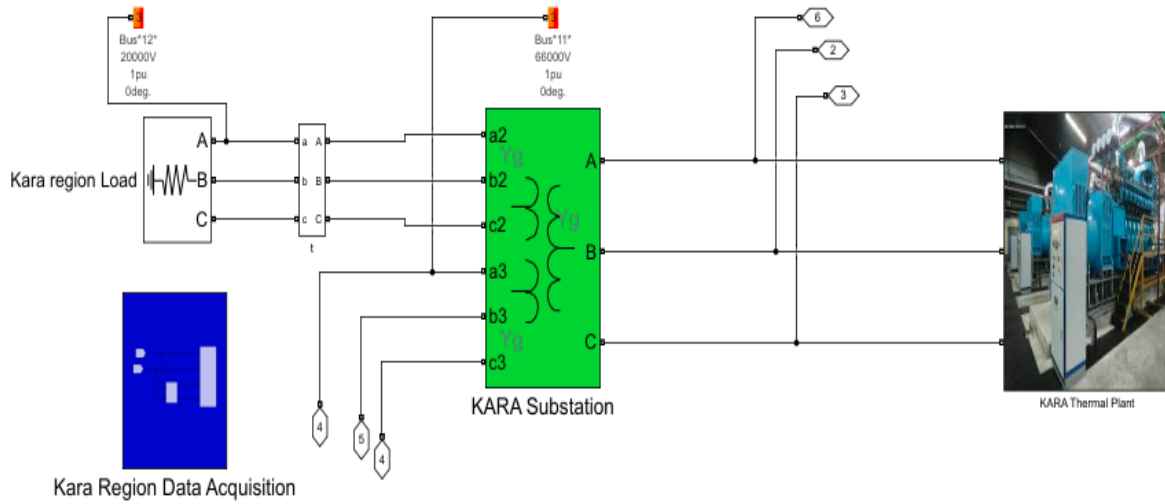


Figure 4-24: Simscape of Kara region power system

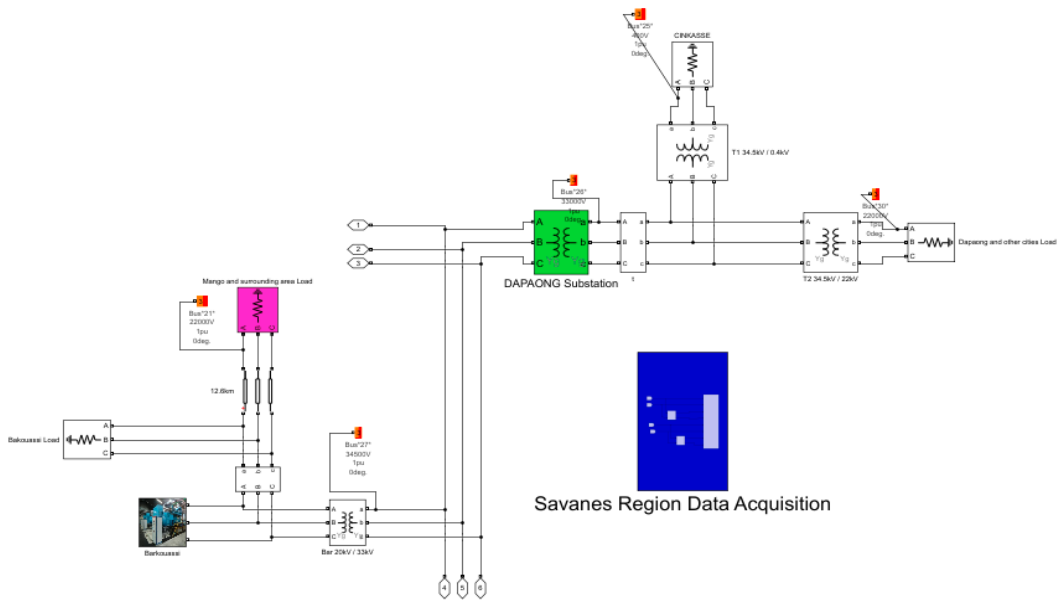


Figure 4-25: Simscape of Savanes region power system

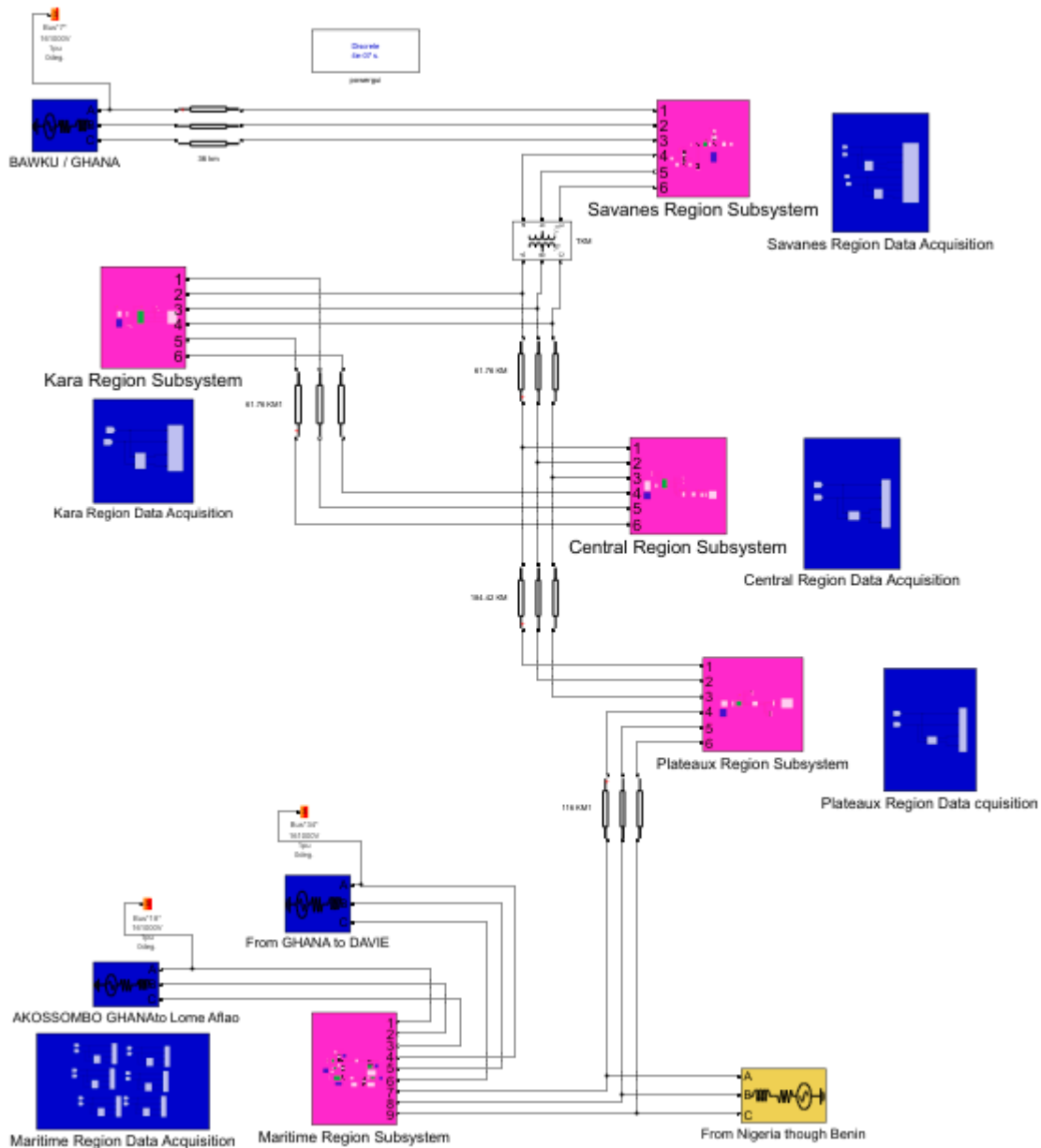


Figure 4-26: Simscape of Togolese national power systems

4.5.3 Togolese power systems Simscape model simulation

Two states of operation baseline data from the grid have been collected from the utility company for December 6th, 2022, respectively, at 9:00 AM and 3:00 PM. These data represent a snapshot of the TIN at the given time. They clearly present the status of the plants in operation, the power produced by each plant, the active power of the loads, voltage, and frequency on each busbar. The utility company CEET uses a SCADA system to monitor and collect data from the grid. Unfortunately, some data were not available at the time of this study. Therefore, the present data concern only those that were available. Table 4-10 summarizes the available data collected from by the state own company in charge of electricity distribution and used to simulate the model . At 9:00 AM, the total power produced by the local power plants throughout the TIN

was 111.26 MW from Kpime mini hydro power plant (0.8MW) in Plateaux region, AMEA solar plant (29.61MW) in Central region, Contour Global (15.2MW) and Kekeli Efficient thermal plant (65.8MW) in Maritime, and 23.62 MW were provided by CEB. An amount of 135.2MW of power was imported from Ghana and Nigeria. We could not collect inductance was in service at the time of the measurement information nor collect reactive power neither for power plants nor for loads.

At 3:00 PM, the total power produced by the local power plants throughout the TIN was 113 MW from Kpime mini hydro power plant (0.8MW) in Plateaux region, AMEA solar plant (29.61MW) in Central region, Contour Global (15.2MW) and Kekeli Efficient thermal plant (65.8MW) in Maritime, and CEB supplied 18.06MW. An amount of 146.3MW of power was imported from Ghana and Nigeria. No inductance was in service at the time of the measurement and we could not collect reactive power neither for power plants nor for loads.

Table 4-11 provides the simulation voltage during the two period.

Table 4-10: CEB & CEET Operating Data on December 6, 2022 at 9AM and 3PM

Date		12/6/2022	
Hour		9AM	3PM
Substations		Load (MW)	Load (MW)
Lome AFLAO	T1	34	41
	T2	30	32
	T3	23	25
Lome Port	T5	26	28
	T6	19	21
	T7	19	20
LEGBASSITO		15	16.8
DAVIE		21.58728	12.43792
ANFOIN		8.45	7.25
TABLIGBO		2.4	2.3
MOME HAGOU		10.85	9.55
ATAKPAME		6	6.4
SOKODE		3.8	4.5
KARA		12.2	14.6
CINKASSE		1.3	1.3
DAPAONG		3.6	3.75

Table 4-11: Simulation voltage vs observation voltage

Substations	9AM voltage(pu)		3PM voltage(pu)	
	CEB & CEET data	Simulation data	CEB & CEET data	Simulation data

Lome	T1	1	0.9929	1	0.9881
AFLAO	T2	1	0.9947	1	0.9921
	T3	1	0.9913	1	0.9941
Lome Port	T5	1	0.9899	1	0.9886
	T6	1	0.9896	1	0.9886
	T7	1	0.9931	1	0.9909
LEGBASSITO		1	0.9233	1	0.9239
DAVIE		1	0.9236	1	0.9235
MOME HAGOU		1	0.9641	1	0.9643
ATAKPAME		1	1.0054	1	1.0054
SOKODE		1	1.0141	1	1.0139
KARA		1	0.9951	1	0.9912
CINKASSE		1	1.215	1	1.2133
DAPAONG		1	1.2249	1	1.2113

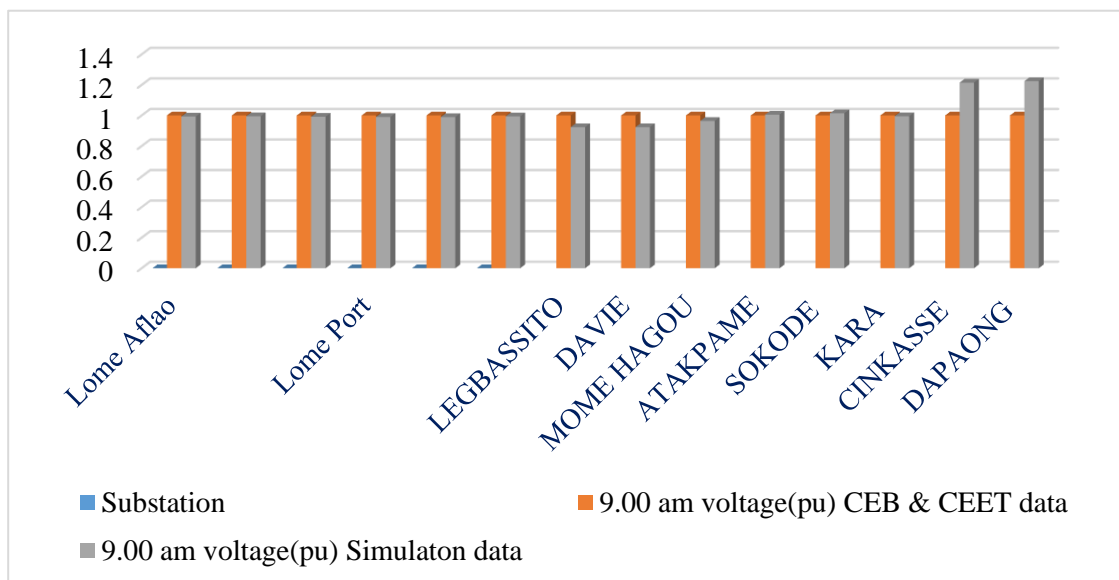


Figure 4-27: Voltage per unit (pu) on different busbar on CEET power system network on December 6th, 2022 at 9 AM.

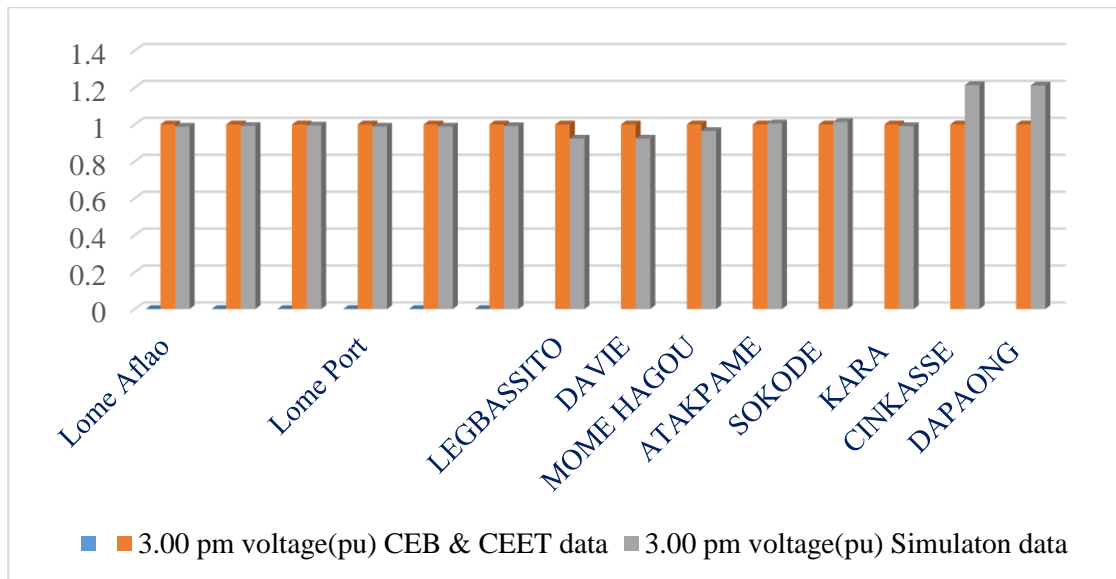


Figure 4-28: Voltage per unit (pu) on different busbar on CEET power system network on December 6th, 2022 at 3 PM.

The simulation voltage falls, as can be seen in Figures 4-27 and 4-28, within the regulation standard limits ($U_{min} = 0.9$ pu; $U_{max} = 1.1$ pu) as reported in (Berndt et al., 2007) except for Dapaong and Cinkasse. Voltage variation may be attributed to many reasons. The latter reason could be attributable to line impedance that could potentially cause a significant voltage drop. Moreover, a voltage drop may occur in the system when the available reactive generation cannot meet the growing demand for reactive power on the customer's side. For long radial feeders, it may not be possible to deliver reactive power, resulting in increased voltage drops at the end user's connection points (Le et al., 2007).

4.5.4 Togolese power network transformation

Transforming the TIN is a necessity and would require a lot of investment in financial, technical, policy, and regulation development. System planning and a roadmap for the transformation of the system are other key factors. In addition to the Togolese government's plans to increase home solar power systems and expand the grid, we suggest that the TIN should follow the roadmap for continuous transformation. This will enable the TIN to become smarter.

1) Digitalization of the distribution subsystem.

This subsystem could be transformed through automation of the distribution substation, distribution control center digitalization, and the introduction of advanced metering infrastructure (AMI) for smart meter utilization at the end-user's side. This could gradually replace the mechanical and prepaid meters currently used in the country.

2) Raising consumers' awareness programs regarding all the opportunities and benefits of energy efficiency (EE). We recommend the implementation of EE measures suggested in (Amega et al., 2020).

3) Digitalization of Communication system.

Introducing ICT into the communication system plays a key role in the smart grid. Therefore, we believe that the sector should be digitalized to make communication between actors and control centers more flexible and easier.

4) Transmission transformation

The transmission subsystem could also be transformed as suggested in Table 4-12. High voltage direct current (HVDC) implementation and automation of the transmission control centres and substations for better monitoring on-site and/or remotely could help improve the quality and reliability of the power transmission across the country and region.

5) The main grid should be connected to all isolated mini-grids for better management of power. Such an implementation serves both as backup energy from the main grid in case of disruption and as an export of surplus power to the main grid. Doing so would result in maintaining the balance between supply and demand in targeted areas.

6) Strength and sustain the regional power interconnection network. This scheme has the potential of reducing the investment in storage systems regarding the RE system amidst the energy mix. A country can export / import power whenever necessary.

Table 4-12:Transmission sector transformation

Components of transformed transmission sector	Sub-components of transformed transmission sector	Description
Control centres smarter	Transmission system monitoring	Data Collection based on SCADA and Phasor Measurement Units (PMUs)(Chow et al., 2007) coupled with wide-area geographical information (GIS).
	Analytical capability	Provision and installation control centres capable of performing dynamic model

Transmission networks smarter	Controllability	updates and validation from cascading failure(P. S. Kundur & Malik, n.d.).
	Interactions with the electricity market	Possibility to conduct real-time studies in place of offline studies for proactive and adaptive actions to better combine generation-transmission.
	Ensure high efficiency and quality in the transmission networks by using high-capacity AC and DC facilities	The electricity market is included in power systems and designed and regulated to meet efficient electricity standards.
	Ensure robustly and self-healing and transmission	Usage of advanced power electronics such as FACTs and HVDC) to ensure flexible controllability and transmission reliability improvement. Usage of solid-state transformers and solid-state breakers in place of traditional electromagnetic transformers and mechanical breakers.
	Advanced transmission facility maintenance	Achieved by using advanced sensing and monitoring of breakers and the transformers.
	Extreme event facility hardening system	Possibility to lubricate the moving parts.
	Digitalization platform	Possibility to prevent extreme events.
	Substations smarter	Fast and reliable sensing, measurement, communication, protection and maintenance of equipment and apparatus installed possible
	Autonomy	Each substation is independent but interconnected with others.
	Coordination	Easy communication with other substations and control centres.
Self-healing	Substation reconfigures itself dynamically.	

4.6 Partial conclusion - 3

This study investigated ways to improve the aging power systems of emerging economies. The Togolese power system was used as an example. To achieve the objective of the study, an expert

elicitation approach was utilized to thoroughly assess the existing power systems. The Togolese power system was modeled in view of smart grid implementation with the help of Simscape-MATLAB/Simulink. Additionally, a roadmap for smart grid development and an oriented-based model for resilient power systems were proposed to not only transform the systems but also improve their reliability and resilience. The findings revealed many problems including heavy dependence on electricity importation, limited production, aging of infrastructures, policy and regulation-related issues, limited coverage of the national grid, limited investment, incentives and power rebate-related issues, and grid code and access issues. The power system needs to be transformed through the transformation of existing systems to provide solutions to the aforementioned issues. Accordingly, the oriented-based model for power resilience was proposed as a temporary solution. A solution-based model could enable the entire power system to be redesigned into a conducive environment with a solid power management system and a realistic investment plan.

General Conclusion and Recommendation

Electricity is critical for humankind in many ways. Power is the fuel that powers industries, cars, heating and cooling devices as well as cooking appliances and lighting. The life of a society without electricity would be limited because they cannot achieve a lot and therefore their quality of life would suffer. The usefulness of electricity is universally acknowledged. It is unfortunate that people still lack access to electricity across the globe. It is so gloomy in Sub-Saharan African countries like Niger, Nigeria, and Togo that the majority of the population is without access to electricity. Togo is facing interrelated power issues, such as limited access to electricity, insecure and unreliable power supply, aging infrastructure, and the impact of a changing climate.

It was the aim of this study to find ways to promote renewable energy and, at the same time, ensure electrical power resilience and sustainability. To fulfill this objective, an integrated method has been utilized.

The first step involved developing a modified Sandia algorithm to develop data sets that covered a typical year. This was done to address the problem of data scarcity and quality in Togo and beyond. This problem stems in large part from the scarcity or inadequacy of weather stations for a large area of coverage and the difficulty of storing data.

Secondly, the PV cell temperature of three types of technology (crystalline, polycrystalline, and amorphous) and generation potential had been modeled and simulated in the Togolese weather conditions under two representative concentration pathways, low and high scenarios (RCP 2.6 and 8.5). The aim was to analyze the probable impact of changing climate on solar technology and its potential at administrative regions and national levels.

Thirdly, the Togolese power systems were thoroughly assessed through report analysis, discussion with energy experts in the utility companies (CEET and AT2ER), and the expert elicitation method. To facilitate smart grid implementation, the power systems were also modeled with the Simscape-MATLAB/Simulink tool. In addition, a smart grid roadmap and an oriented-based model were proposed for transforming power systems into intelligent ones.

As a result, the following can be mentioned:

- Typical meteorological year datasets have been developed for RE studies, design, and planning in Togo.
- PV cells' temperature would likely rise over all five regions in Togo and may trigger a decline in the PV potential under RCP2.6 and 8.5. However, the magnitude of the induced

change, brought about with the aid of the altering climate, depended on two foremost factors: (1) PV technology and (2) geographical position. These dissimilarities were more pronounced under RCP8.5 with amorphous technology.

- Issues triggering the Togolese power system included limited supply, discrepancies in policies and regulations, technical issues regarding the transmission, distribution, and off-grid subsystems, limited investment, and a lack of incentives and rebates.
- A Simscape Togolese power systems model has been developed in view of smart grid implementation as well as an oriented-based model for resilient power systems was proposed for the transformation of the aging power infrastructure of emerging economies.

A continual improvement of power systems is vital to meet the increasing electricity demand in affordable and sustainable ways. Doing so would result in a better quality of life and the development of society. To support such a vision, we recommend:

- More investment in acquiring data collection equipment, maintenance and monitoring, data storage, and management. For short and medium-term planning and design of RE, accurate and quality on-ground data would be available.
- An update of energy policy and regulation to allow for pro-consumption as well as a feed-in tariff.
- To intensify the education of the population regarding energy efficiency and energy conservation strategies.
- To take into consideration the impact of a changing climate when designing and planning decentralized energy resources.
- To strengthen and sustain the regional interconnection power network like WAPP to maintain an enabling environment for power export/import, especially in case of high penetration of RE.
- It is important to maintain and sustain strong energy planning and transformation of power systems. This will help improve quality and reliability by prioritizing investments to transform the system step by step.

In future studies, the Togolese Simscape power system model can be updated using complete utility data if they are available. Using this data, we will be in a position to analyze the overall performance of the grid and upgrade it to include more renewable (Wind and Solar) energy. Another study could be conducted focusing on modeling universities, hospitals, and cities, like OUA City, Millennium City, and Mokpokpo City. This will enable the utility to make the power system smarter.

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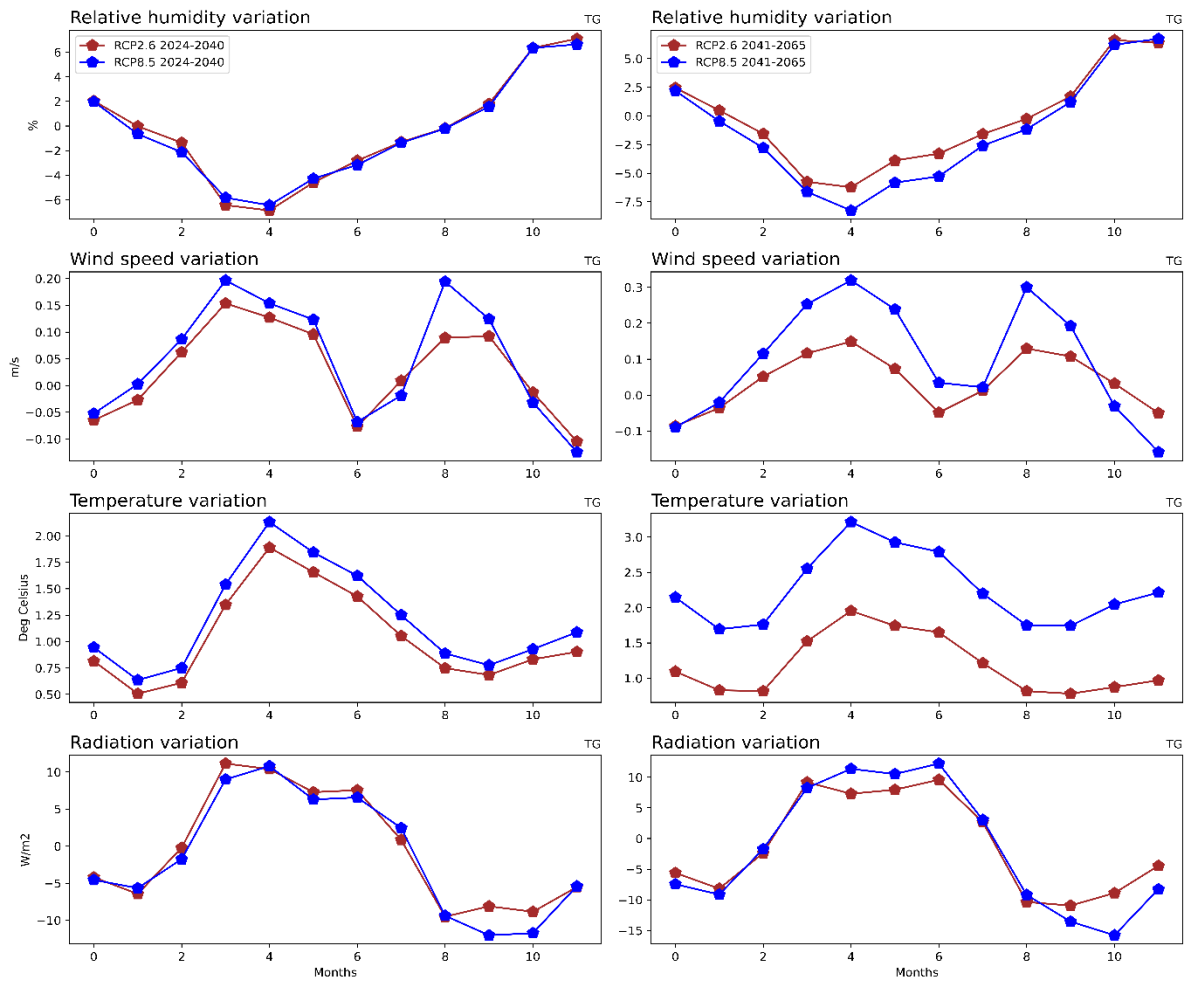
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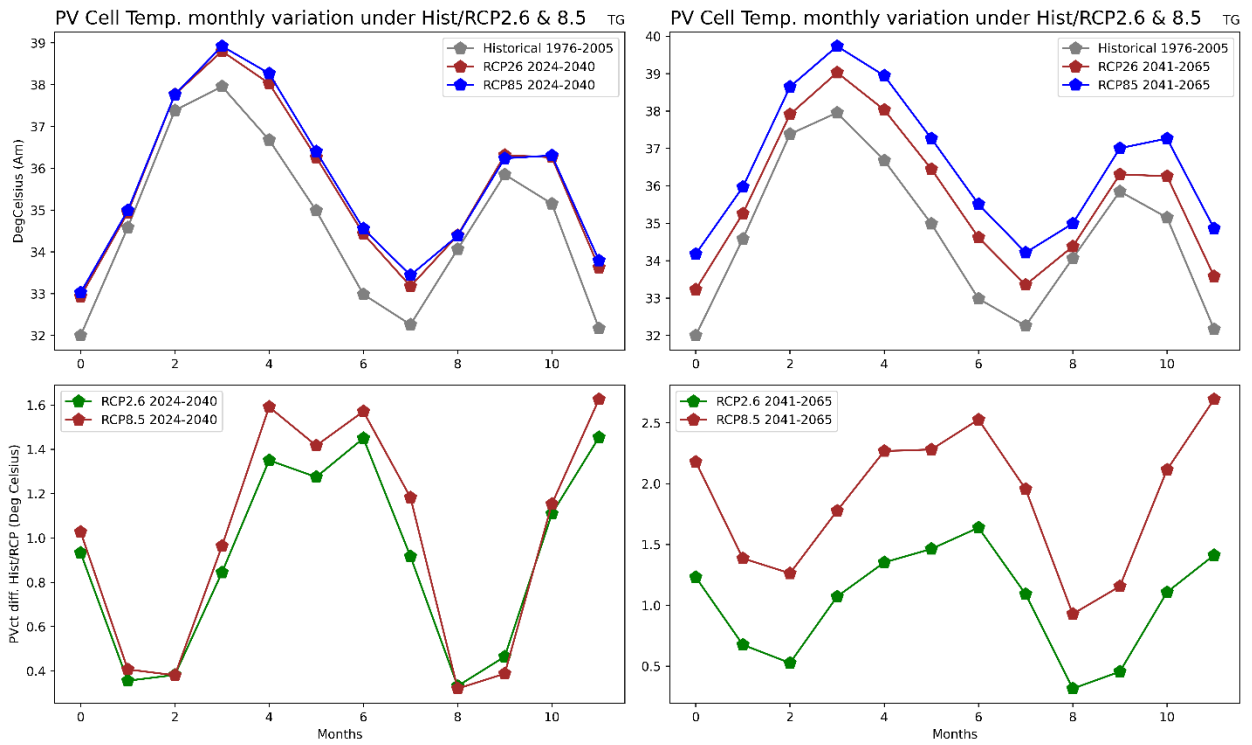
Appendices

Appendix 1: Atmospheric variables variation under RCP2.6 & 8.5 during the near and middle future

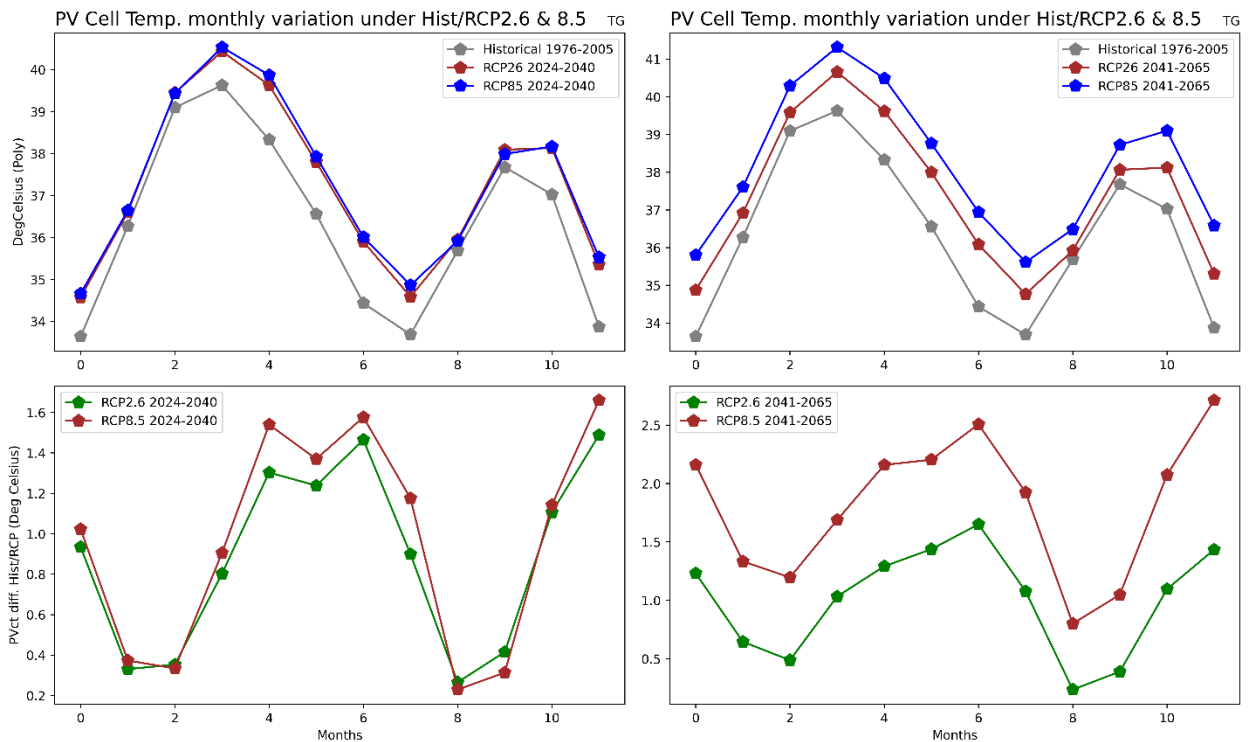


Climatological Variation of Rh, Wspd, Tas and Rds over Togo under RCP2.6 & 8.5 scenarios during 2024-2040 and 2041-2065

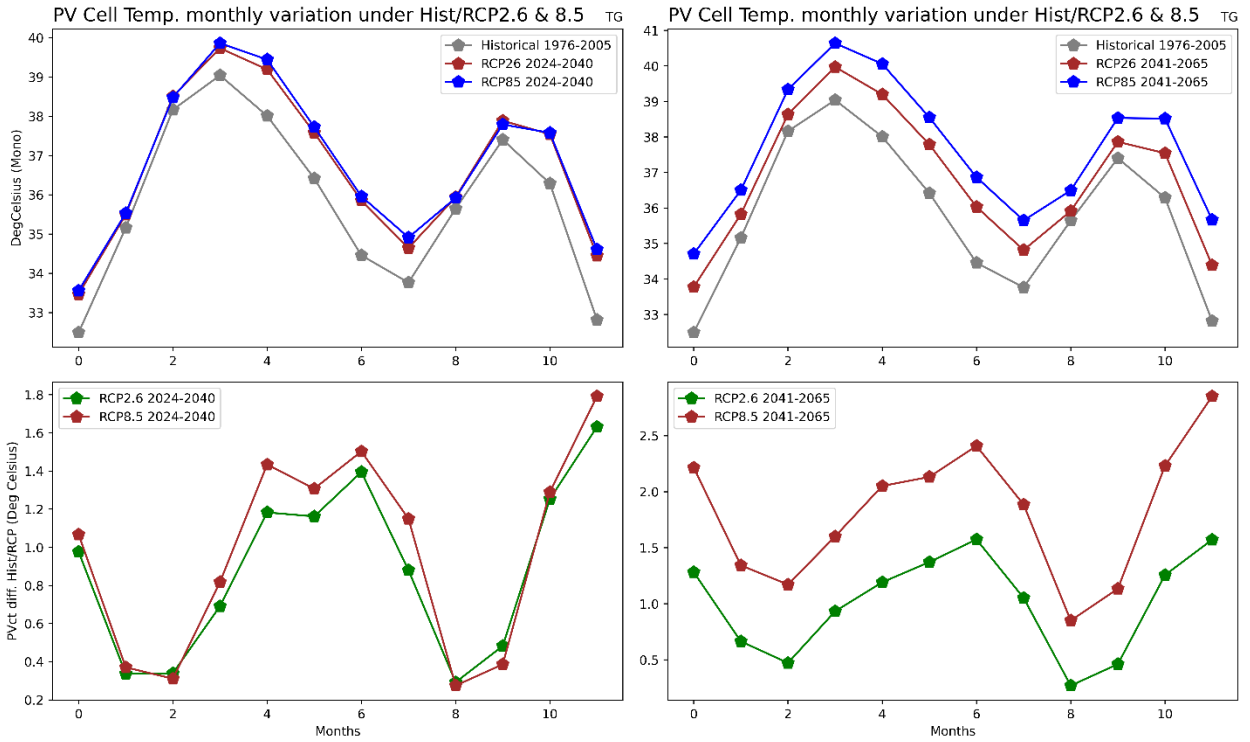
Appendix 2: PVct projected changes over Togo and its administrative regions



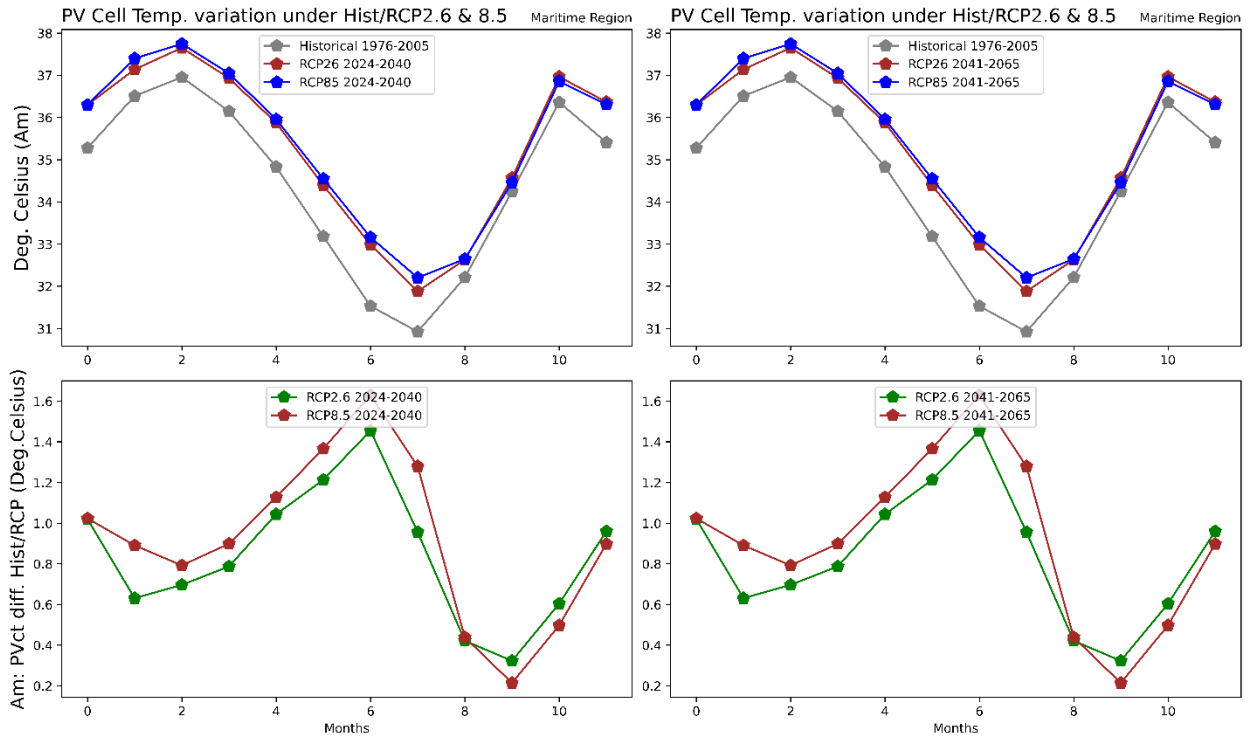
Climatological evolution and variation of Amorphous cell temperature under rcp2.5 & 8.5 over Togo (Country level)



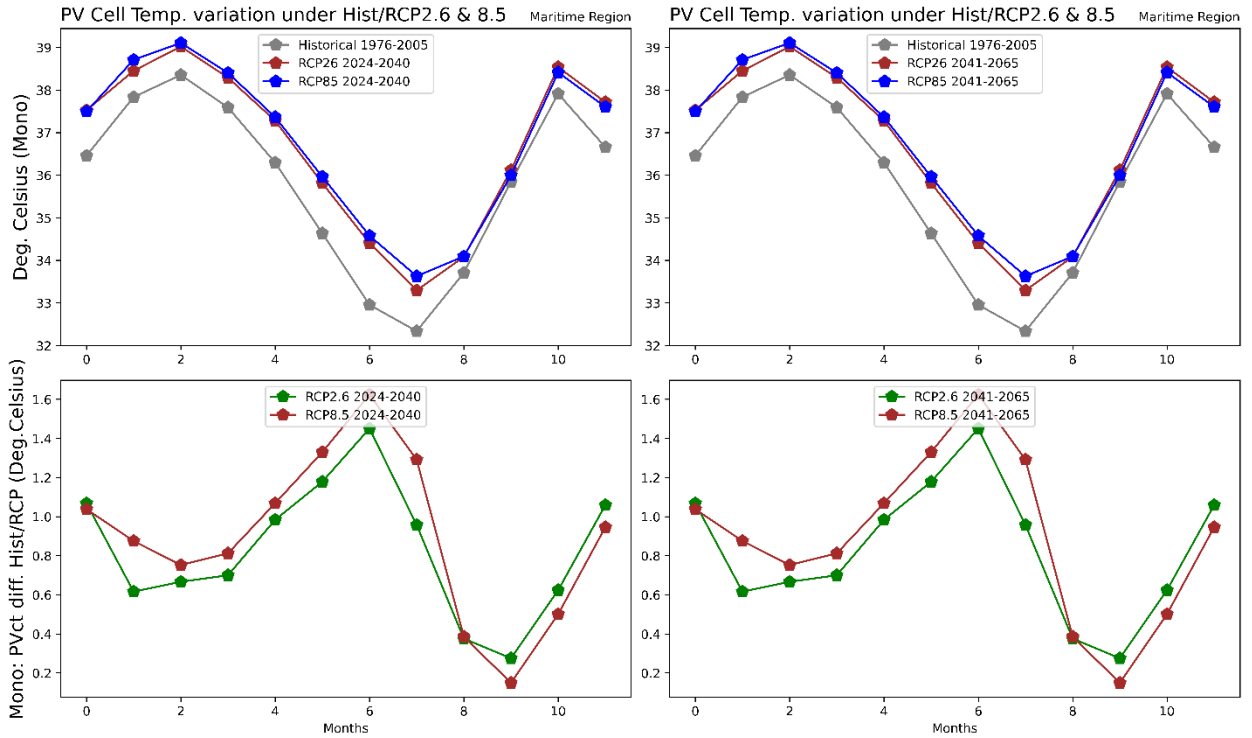
Climatological evolution and variation of Monocrystalline (Mono Si) cell temperature under rcp2.5 & 8.5 over Togo (Country level)



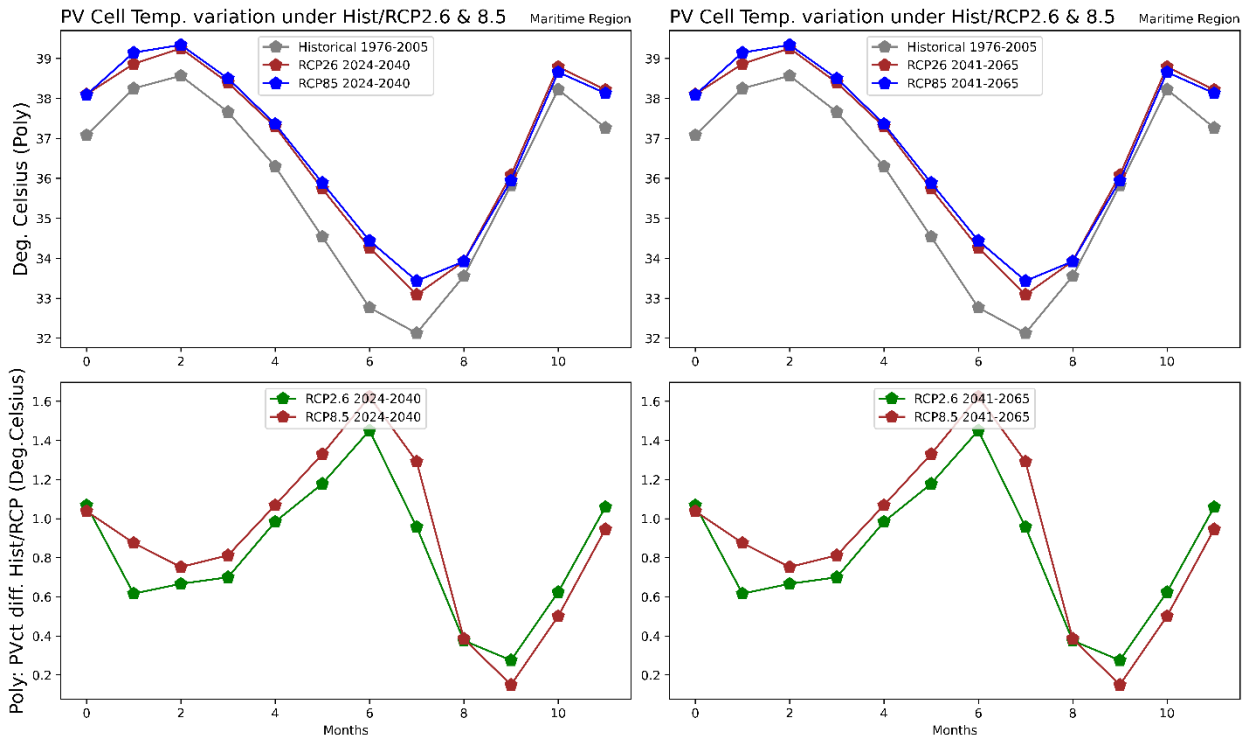
Climatological evolution and variation of Polycrystalline (Poly Si) cell temperature under rcp2.5 & 8.5 over Togo (Country level)



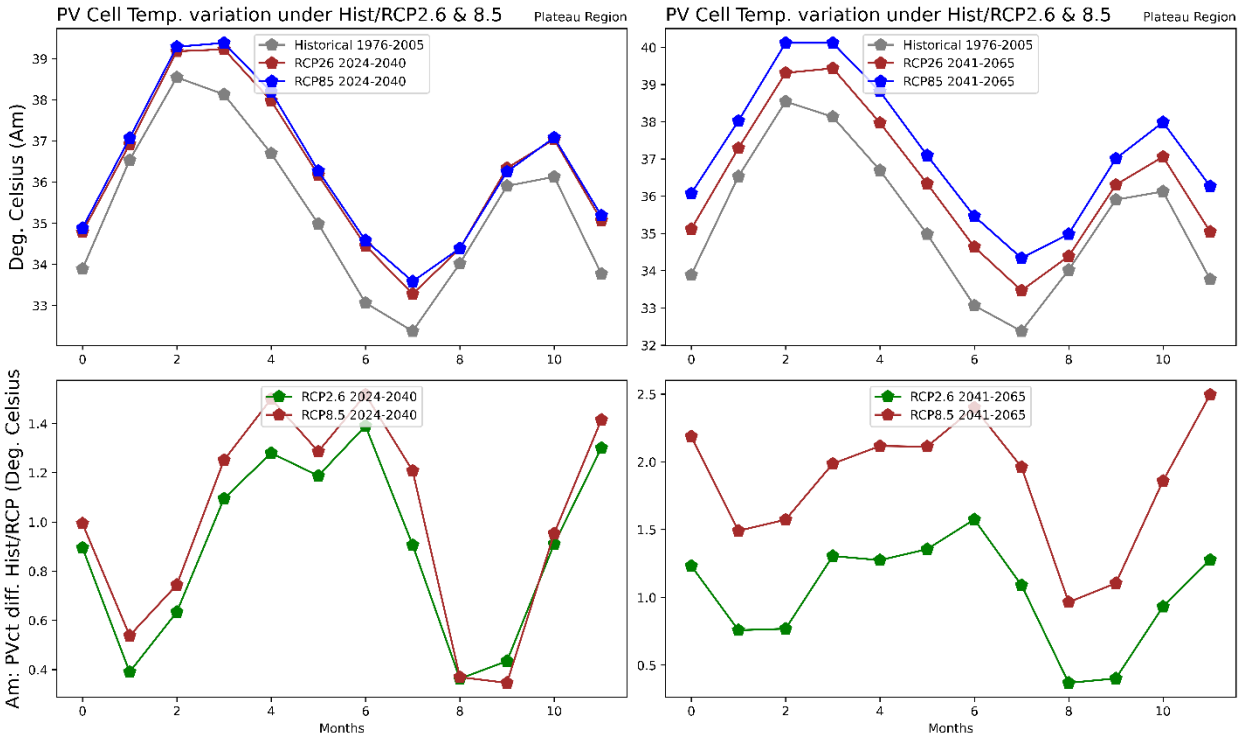
Climatological variation and difference of projected change in PVct from 2024-2065 under RCP2.6 & 8.5 scenarios over Maritime region in relation with Amorphous crystalline cell technology



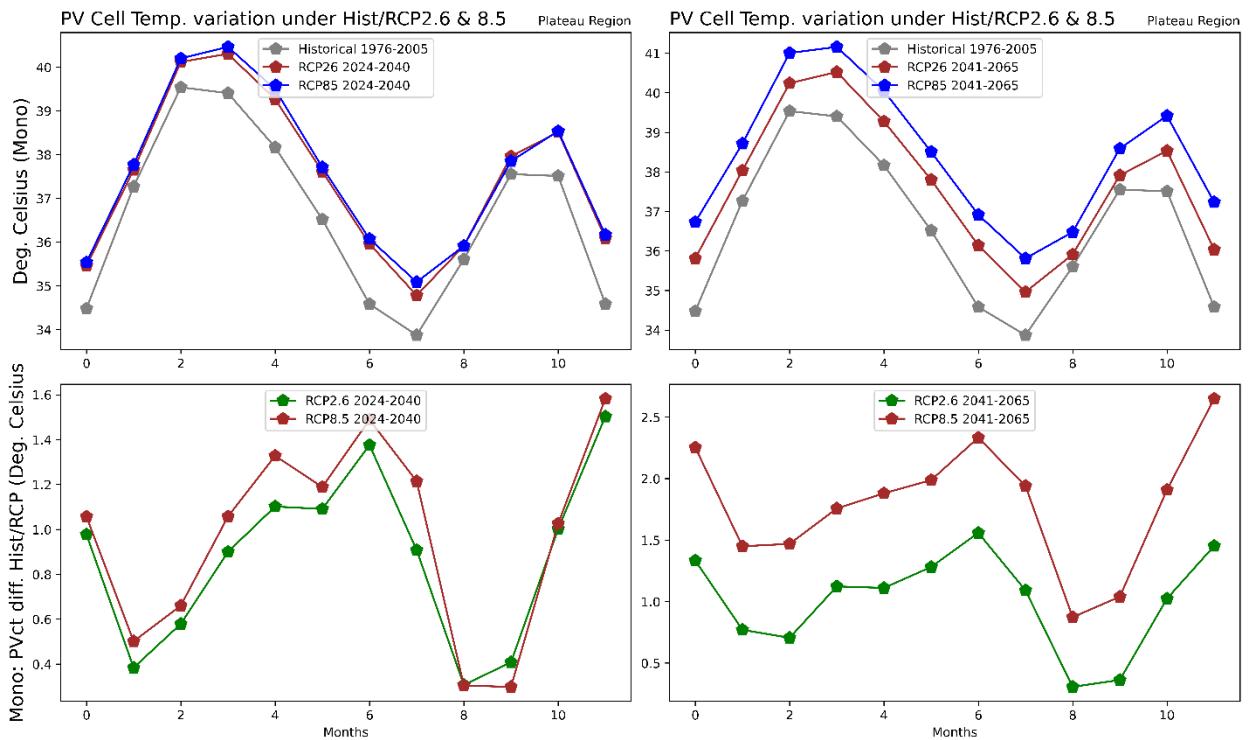
Climatological variation and difference of projected change in PVct from 2024-2065 under RCP2.6 & 8.5 scenarios over Maritime region in relation with Mono crystalline cell technology



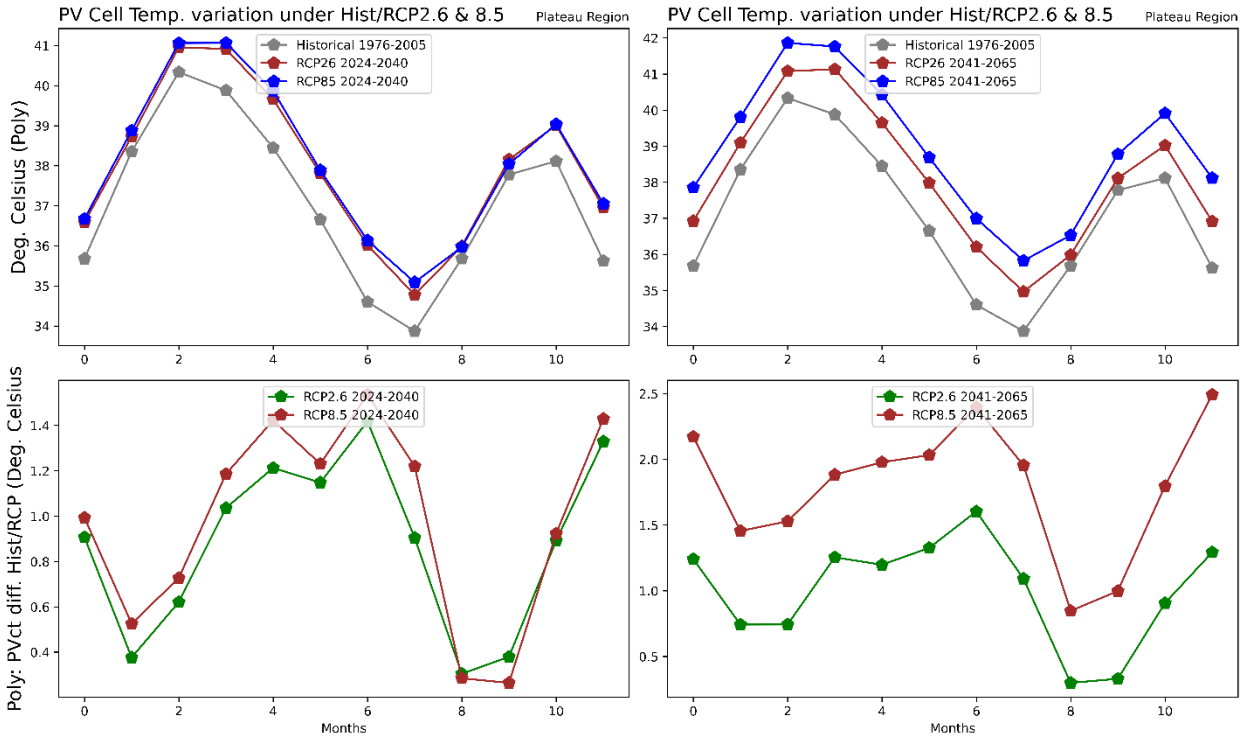
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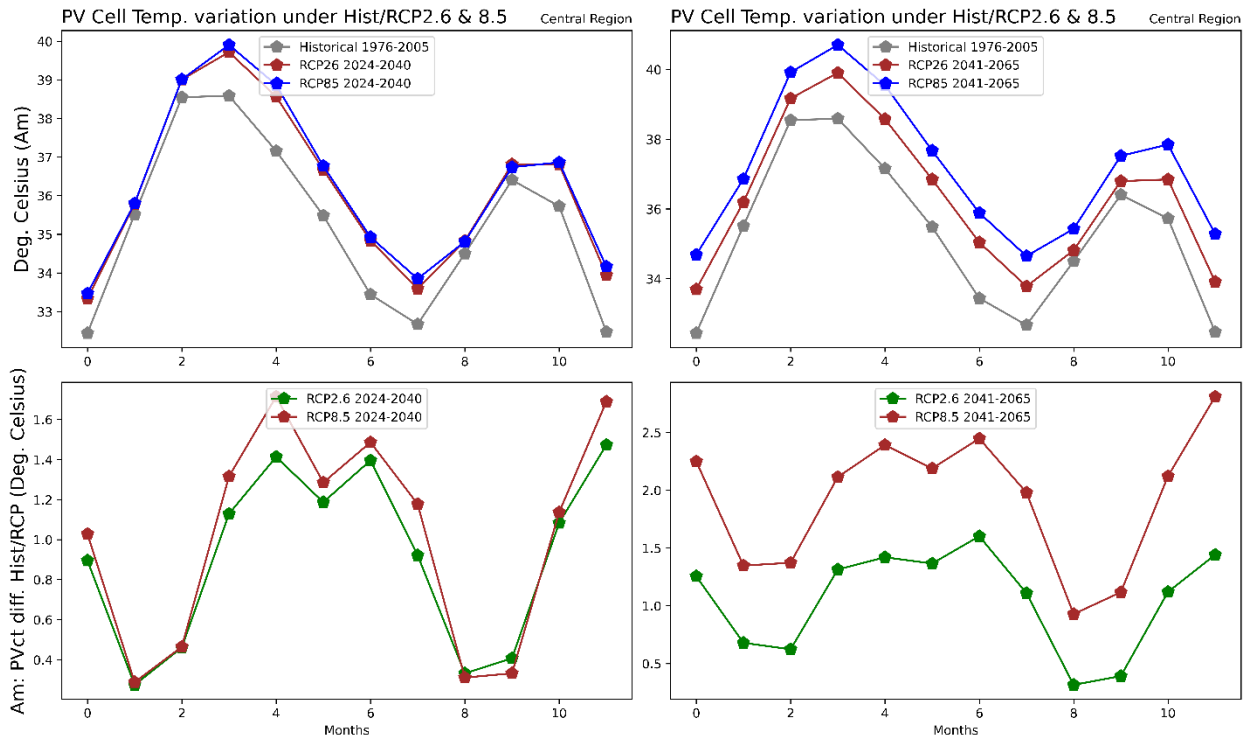
Climatological variation and difference of projected change in PVct from 2024-2065 under RCP2.6 & 8.5 scenarios over Plateaux region in relation with Amorphous crystalline cell technology



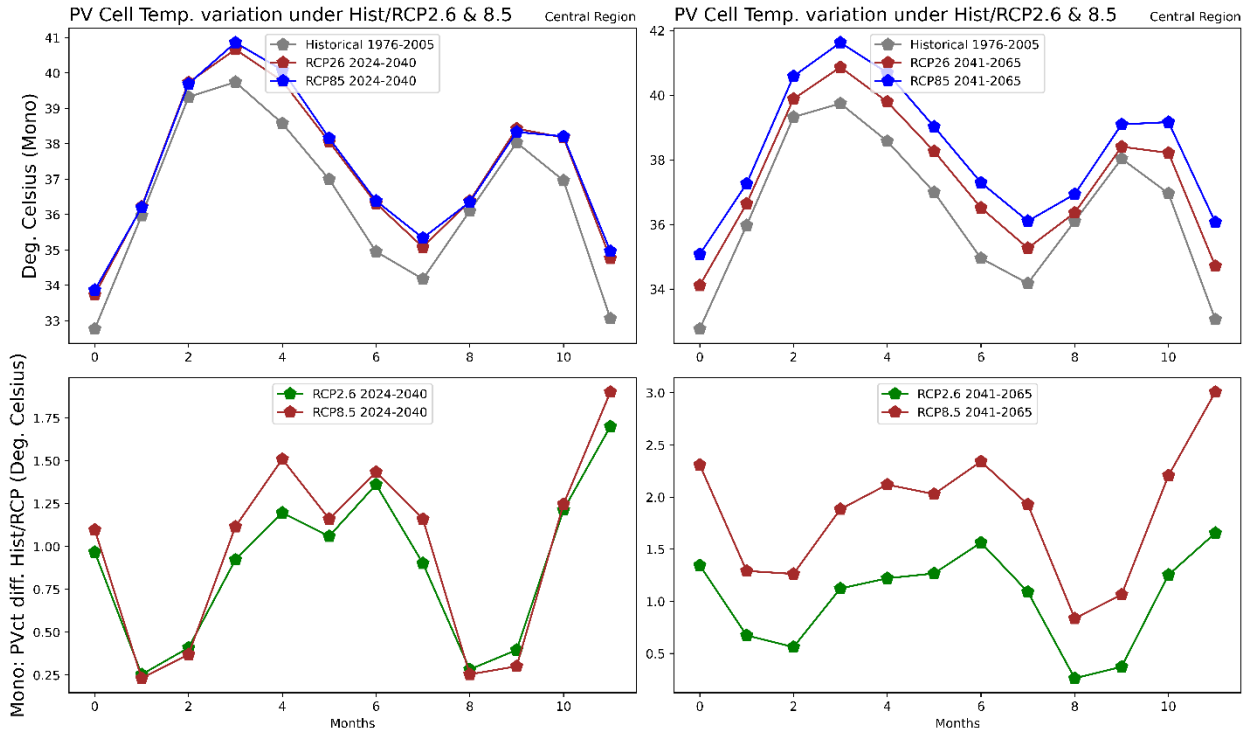
Climatological variation and difference of projected change in PVct from 2024-2065 under RCP2.6 & 8.5 scenarios over Plateaux region in relation with Mono crystalline cell technology



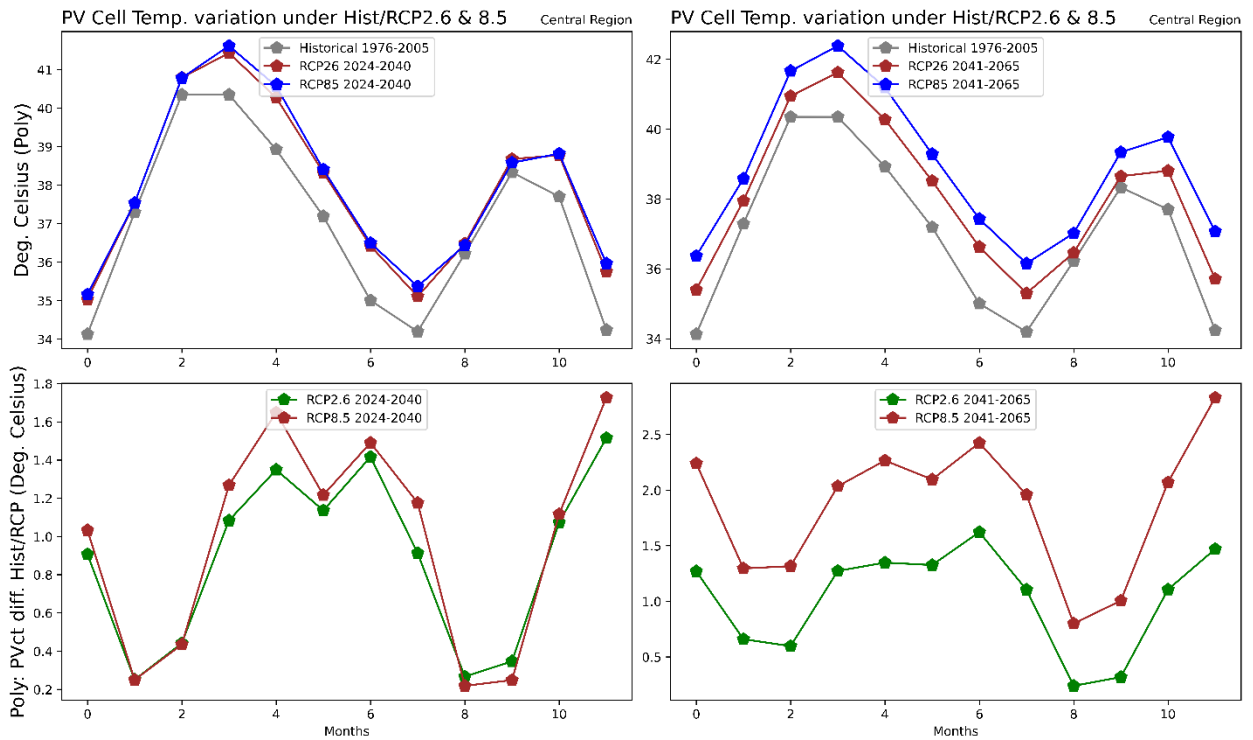
Monthly variation and difference of projected change in PVct from 2024-2065 under RCP2.6 & 8.5 scenarios over Plateaux region in relation with Poly crystalline cell technology



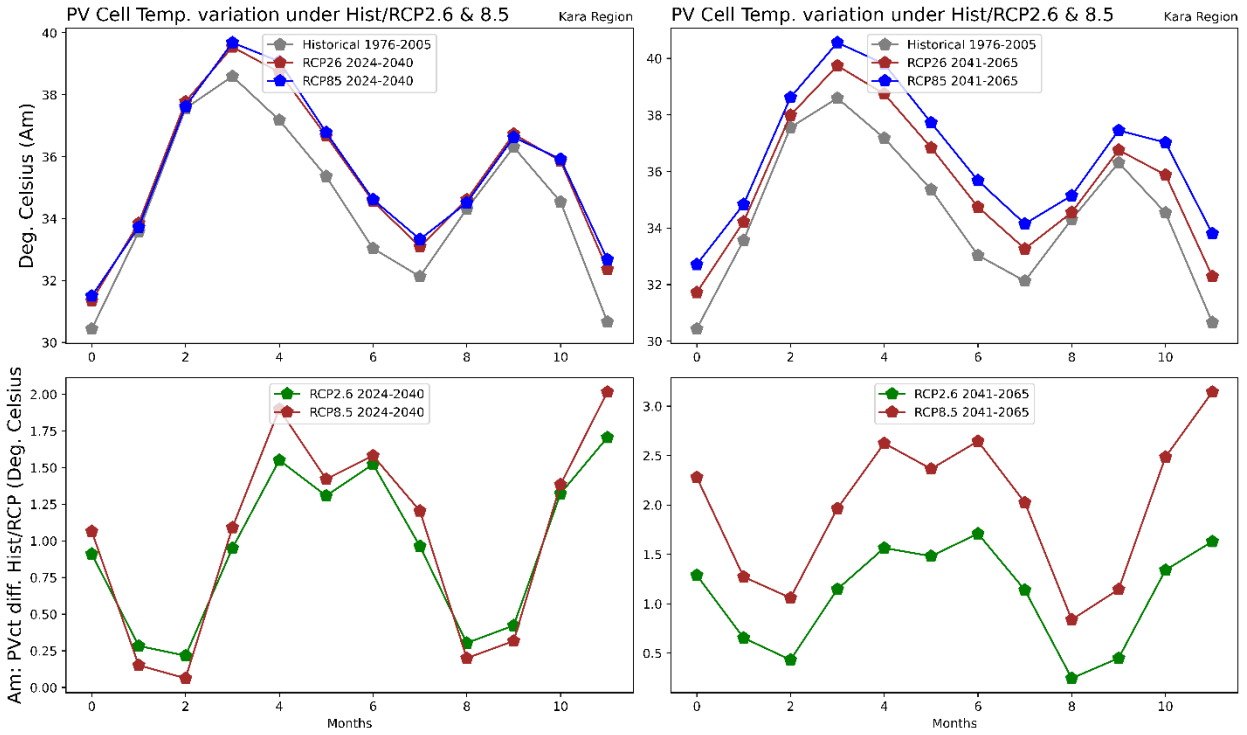
Climatological variation and difference of projected change in PVct from 2024-2065 under RCP2.6 & 8.5 scenarios over Central region in relation with Amorphous crystalline cell technology



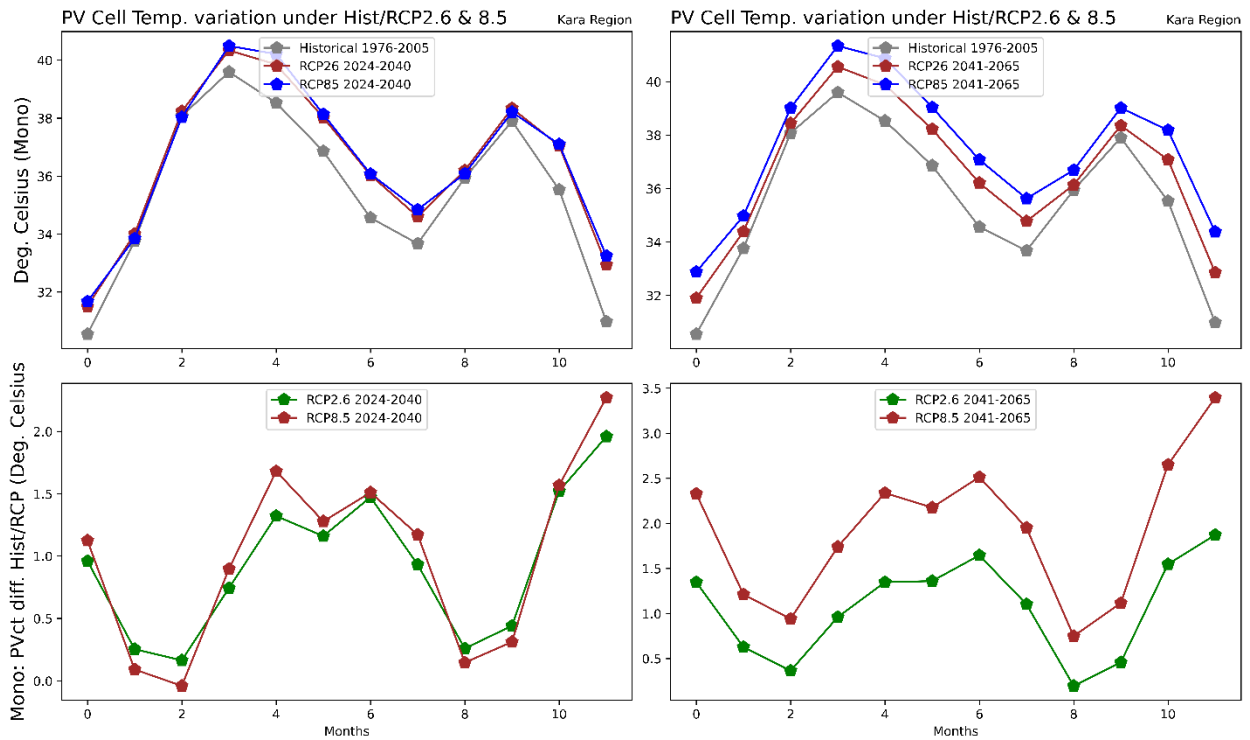
Climatological variation and difference of projected change in PVct from 2024-2065 under RCP2.6 & 8.5 scenarios over Central region in relation with Mono crystalline cell technology



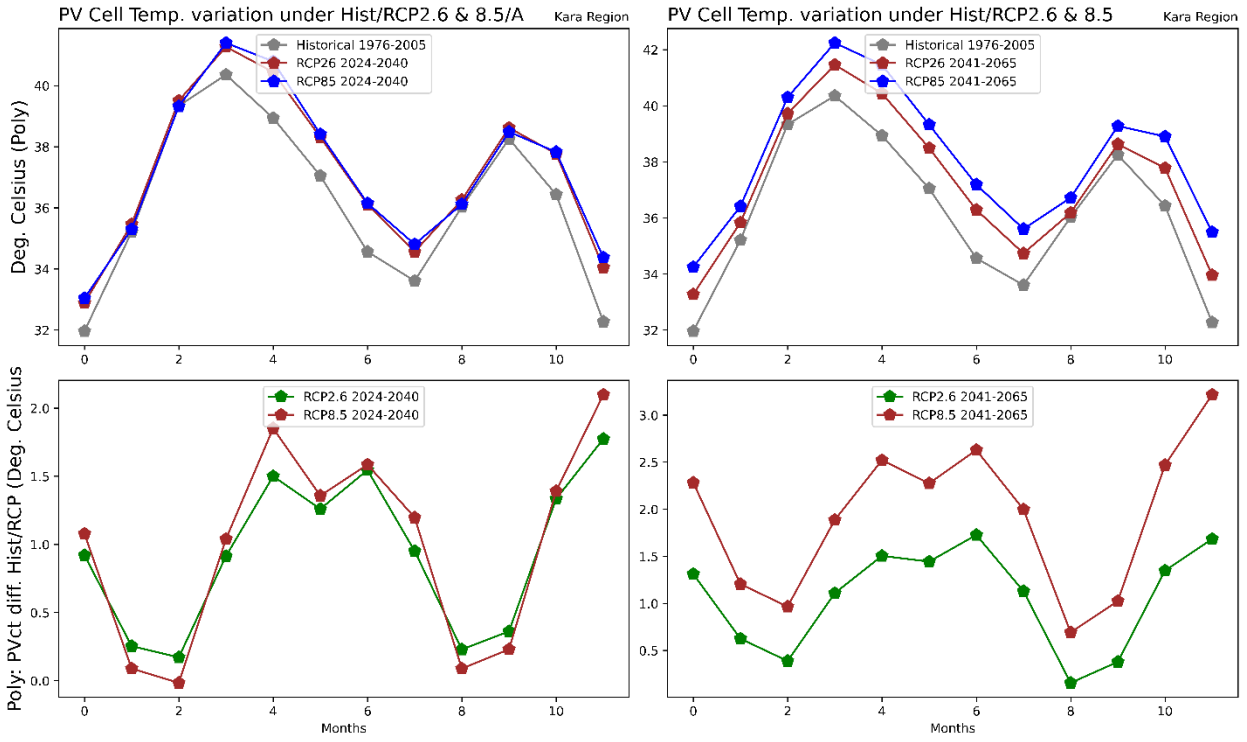
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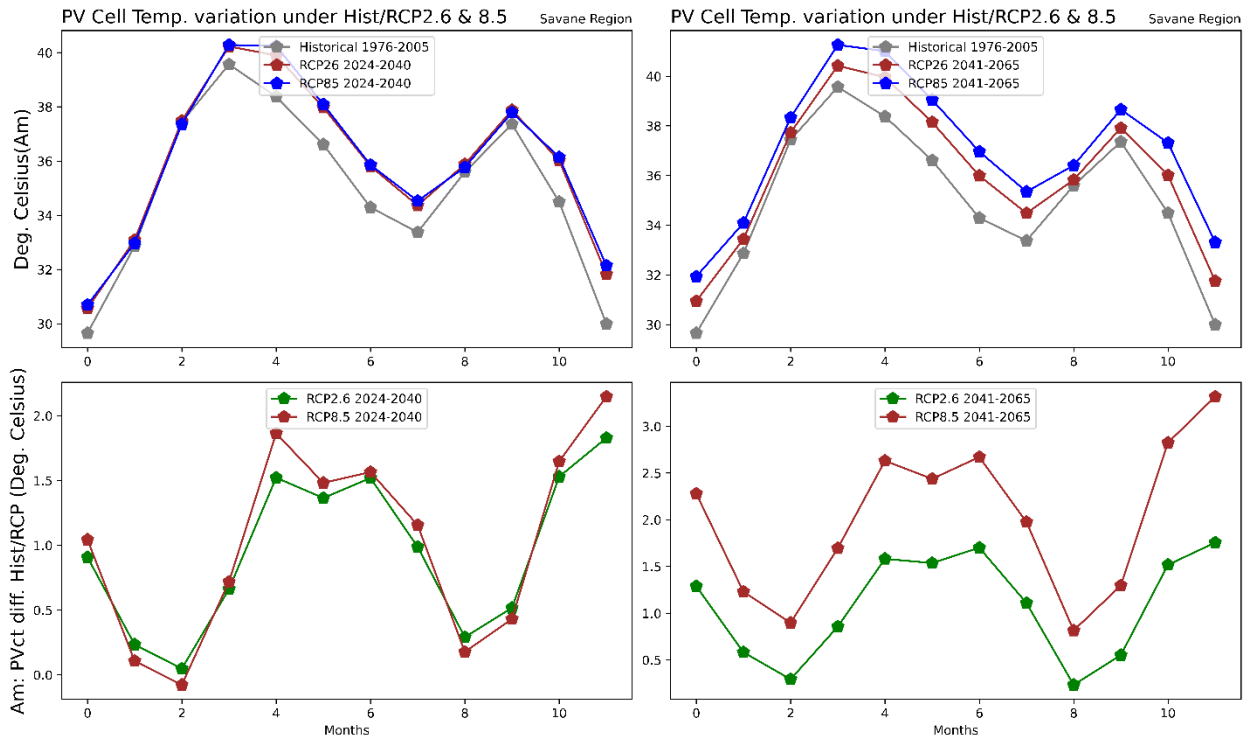
Climatological variation and difference of projected change in PVct from 2024-2065 under RCP2.6 & 8.5 scenarios over Kara region in relation with Amorphous crystalline cell technology



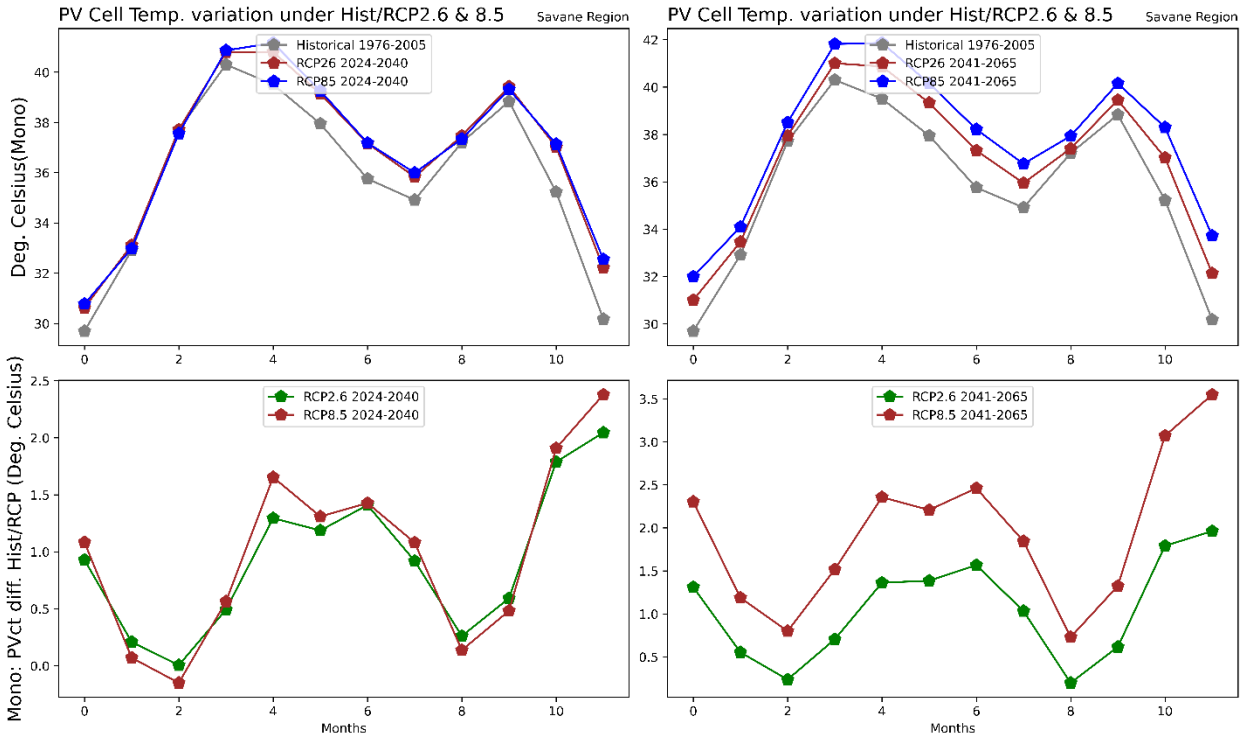
Climatological variation and difference of projected change in PVct from 2024-2065 under RCP2.6 & 8.5 scenarios over Kara region in relation with Mono crystalline cell technology



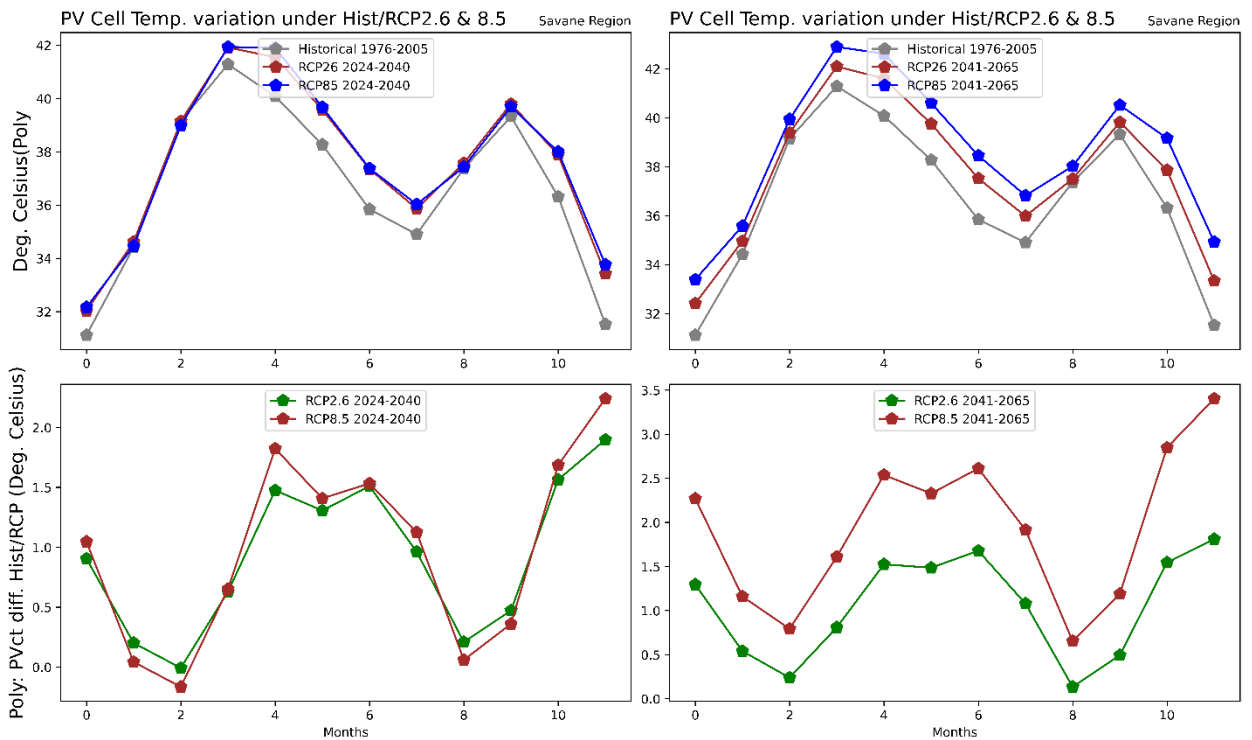
Climatological variation and difference of projected change in PVct from 2024-2065 under RCP2.6 & 8.5 scenarios over Kara region in relation with Polys crystalline cell technology



Climatological variation and difference of projected change in PVct from 2024-2065 under RCP2.6 & 8.5 scenarios over Savannah region in relation with Amorphous crystalline cell technology

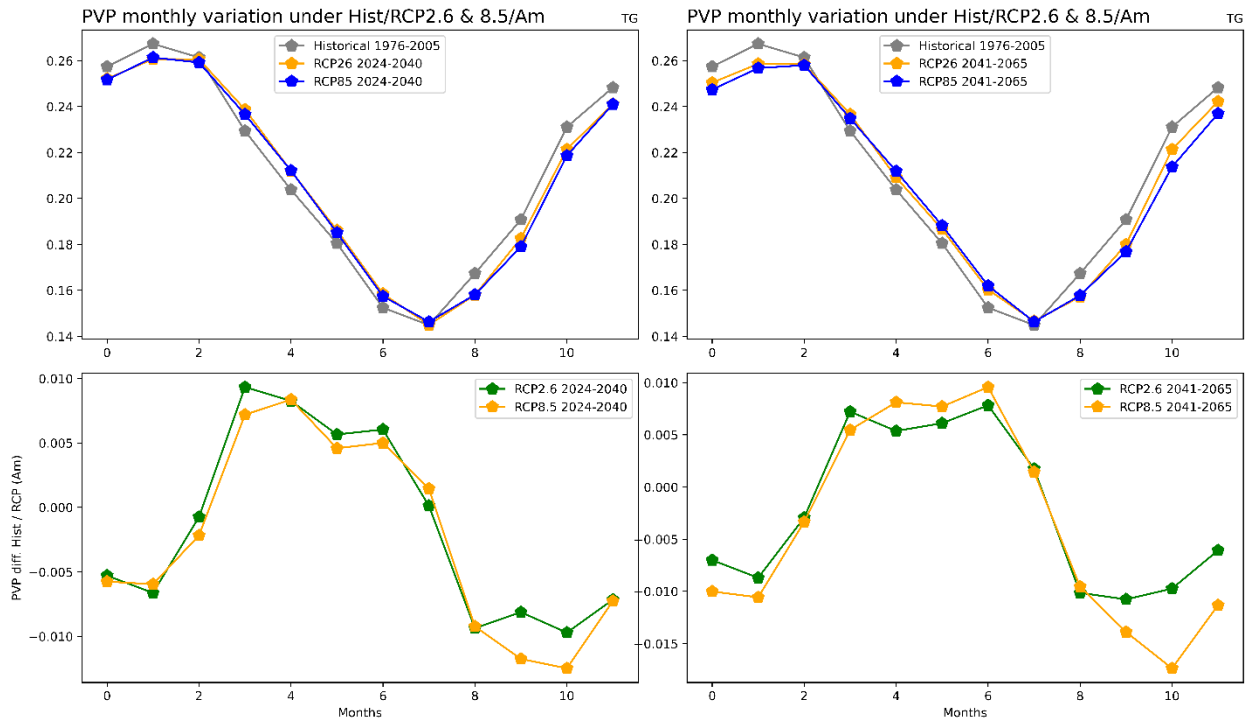


Climatological variation and difference of projected change in PVct from 2024-2065 under RCP2.6 & 8.5 scenarios over Savannah region in relation with Mono crystalline cell technology

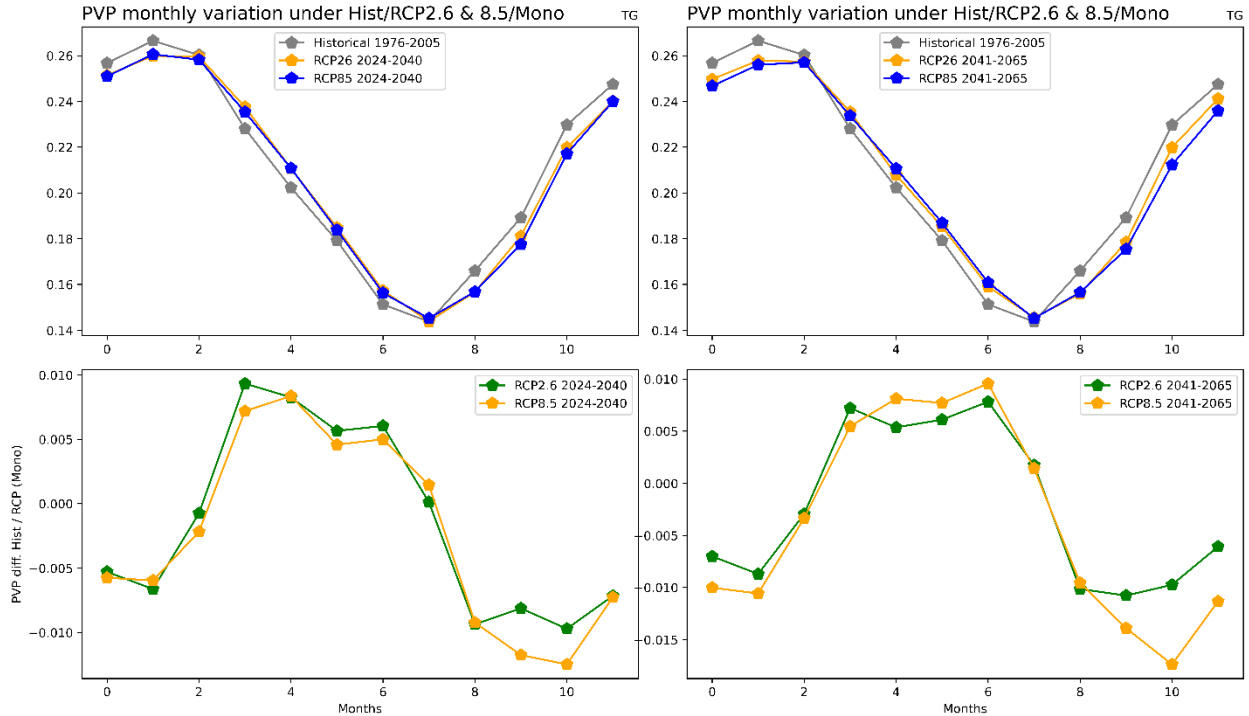


Climatological variation and difference of projected change in PVct from 2024-2065 under RCP2.6 & 8.5 scenarios over Savannah region in relation with Poly crystalline cell technology

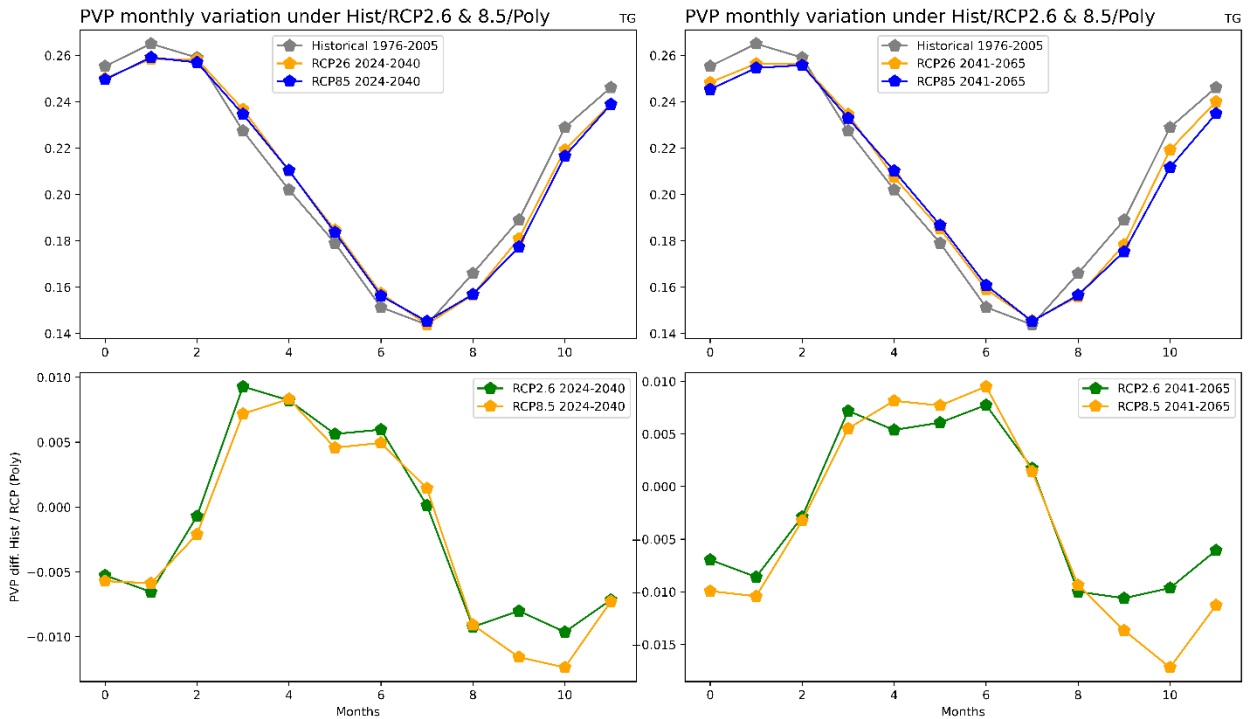
Appendix 3: PVP projected changes over Togo and its administrative regions (Climate change impact on solar energy production in Togo)



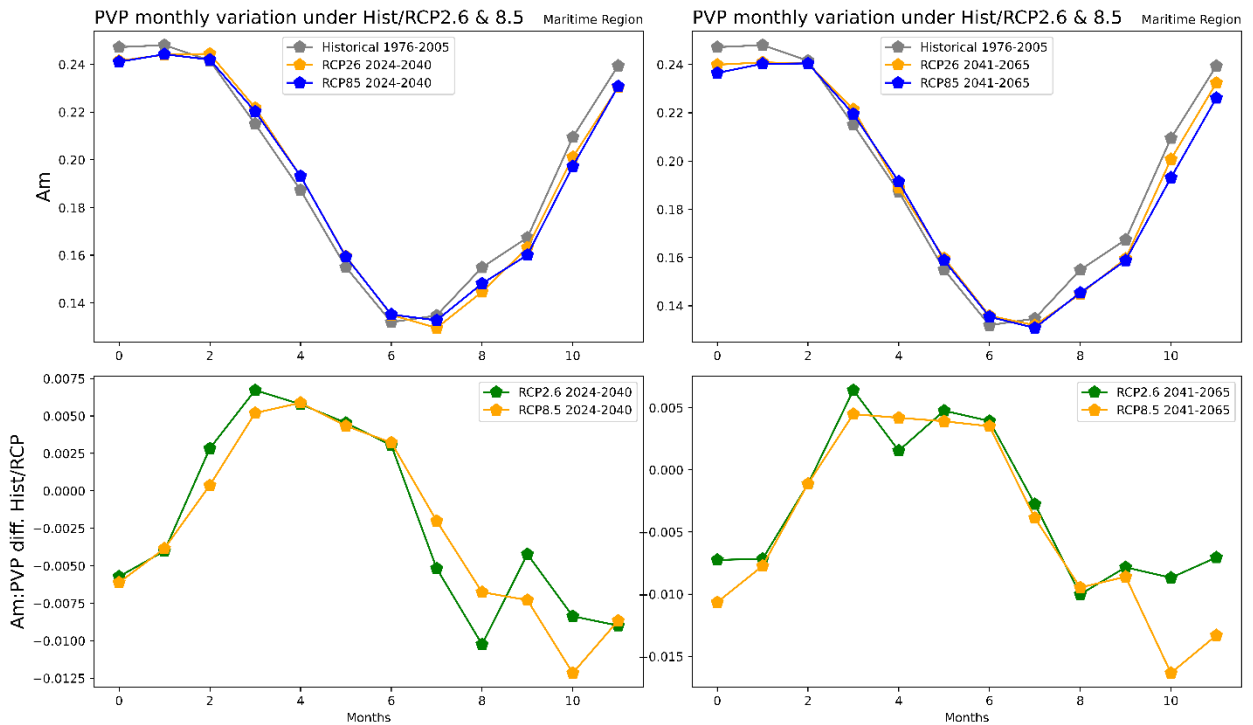
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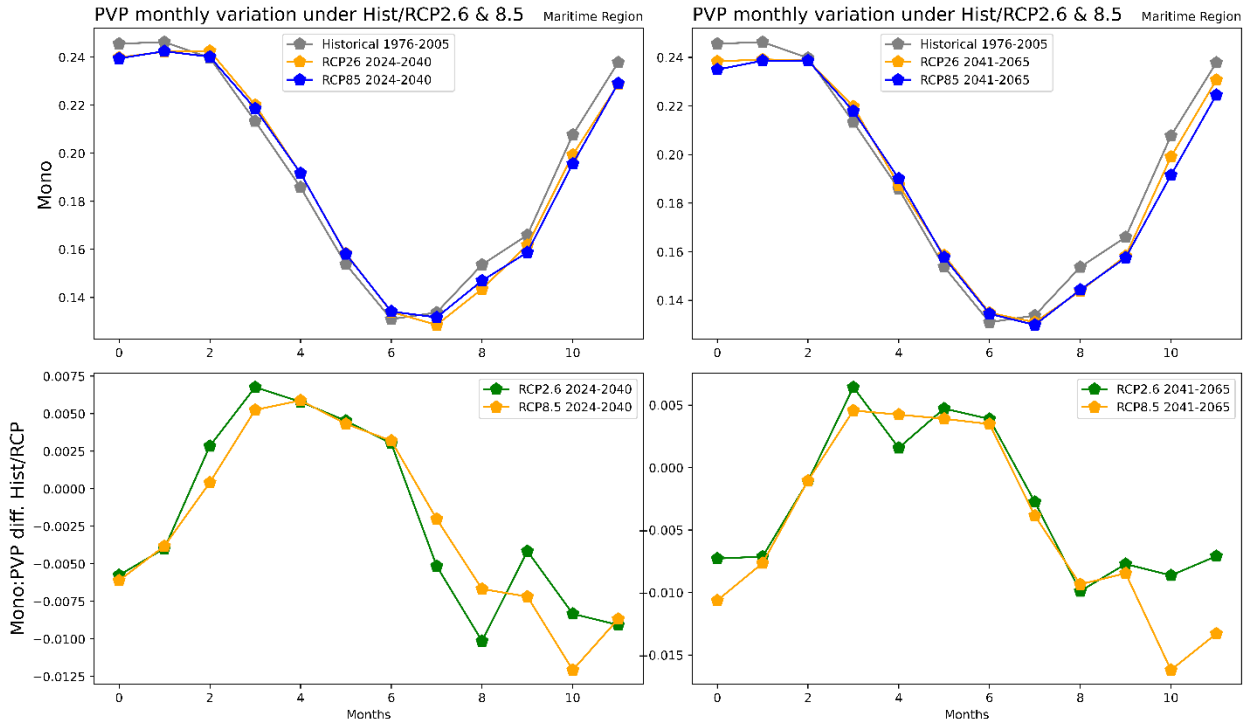
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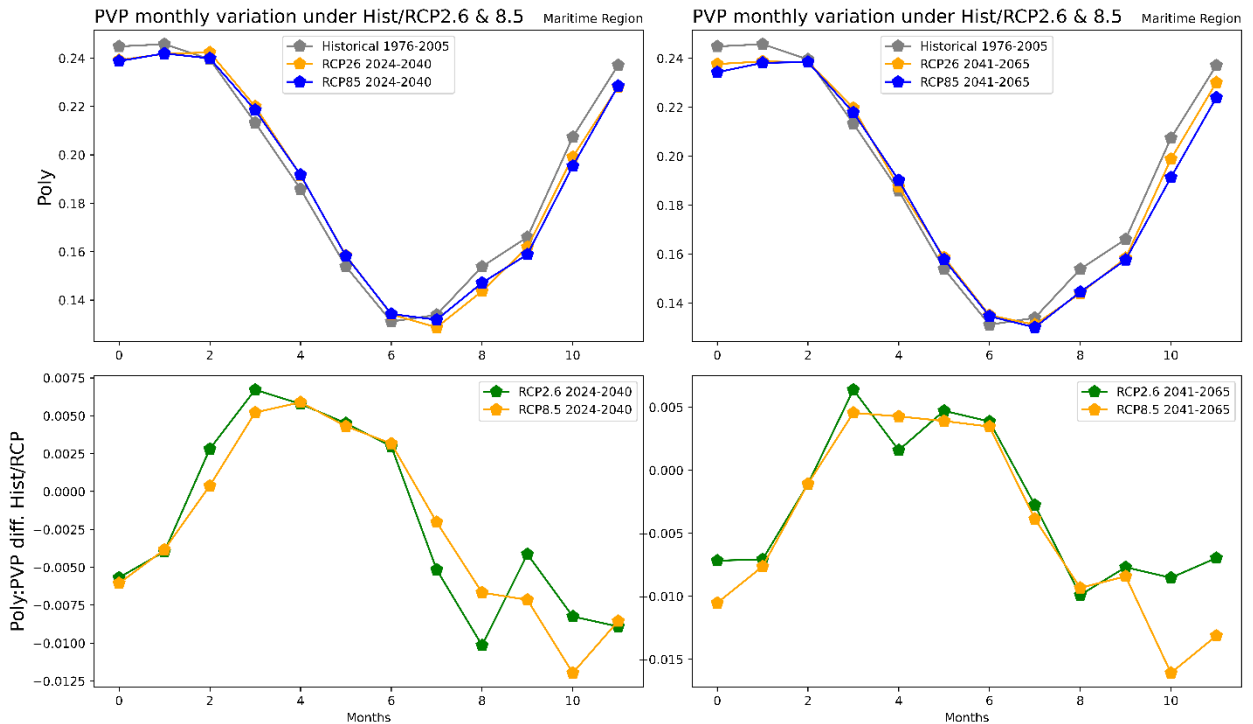
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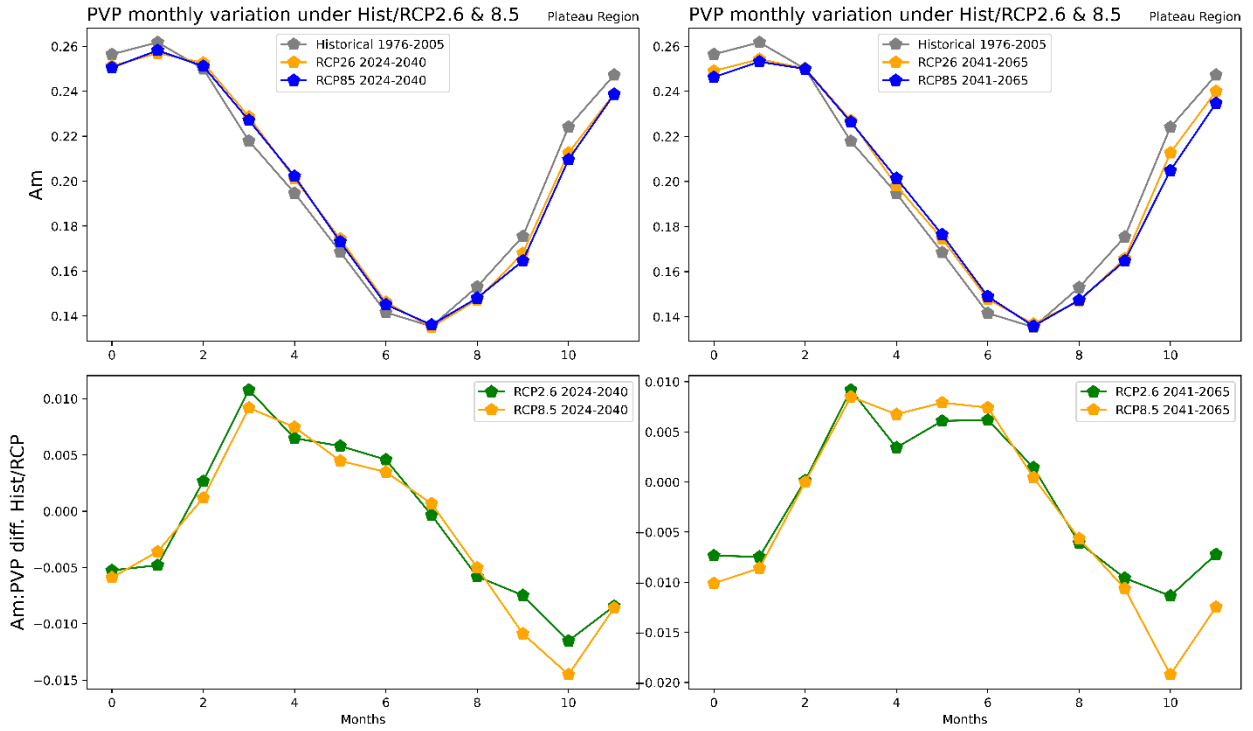
Climatological variation and difference of projected change in PVP from 2024-2065 under RCP2.6 & 8.5 scenarios in relation with Amorphous crystalline cell technology over Maritime region



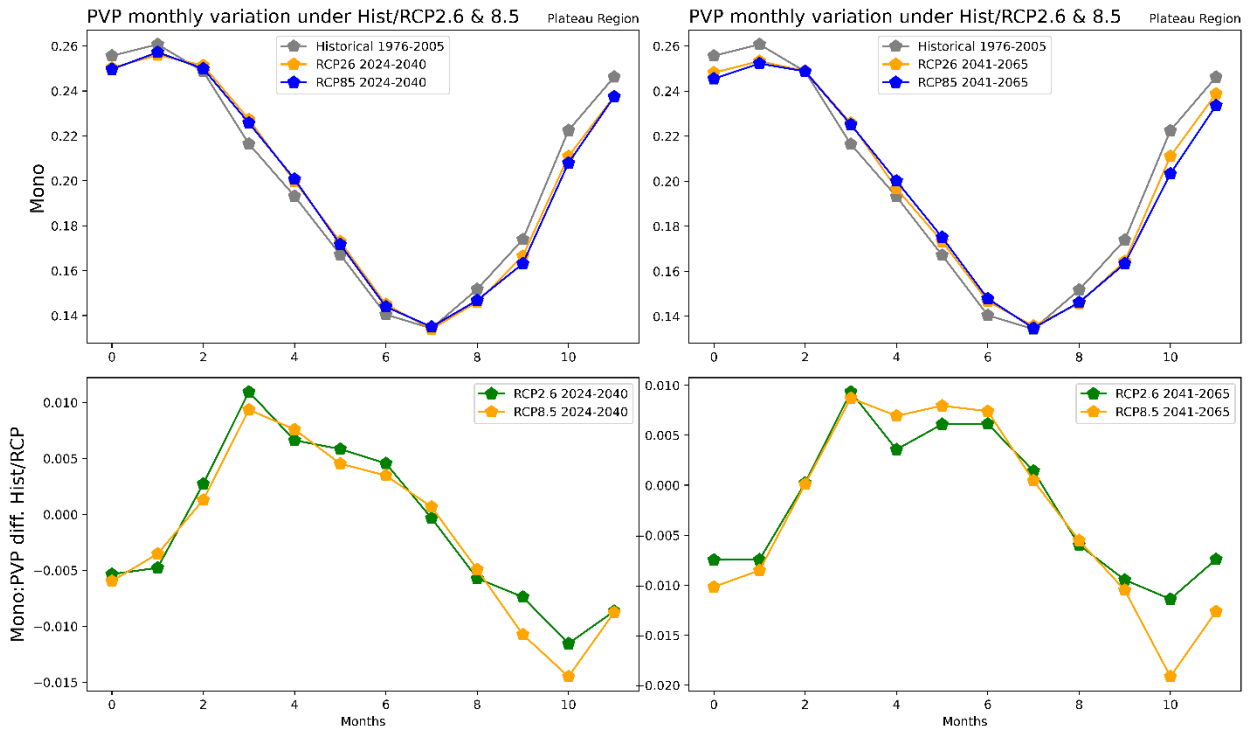
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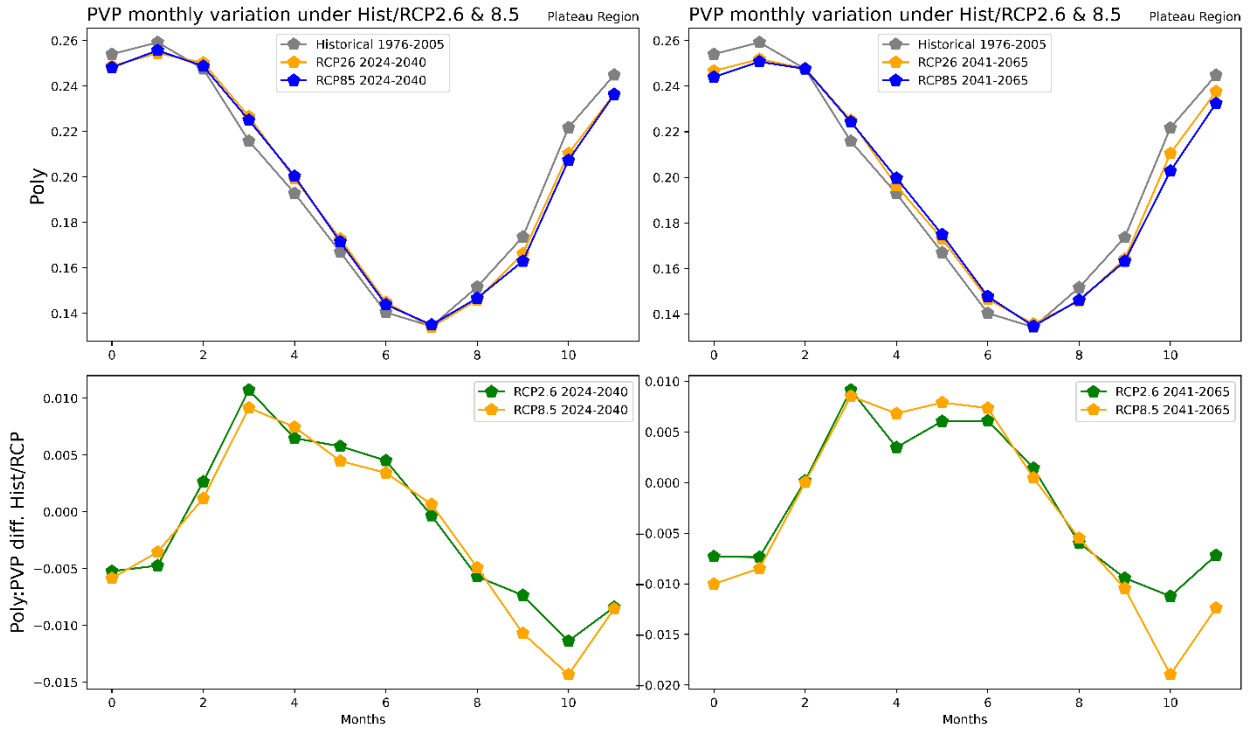
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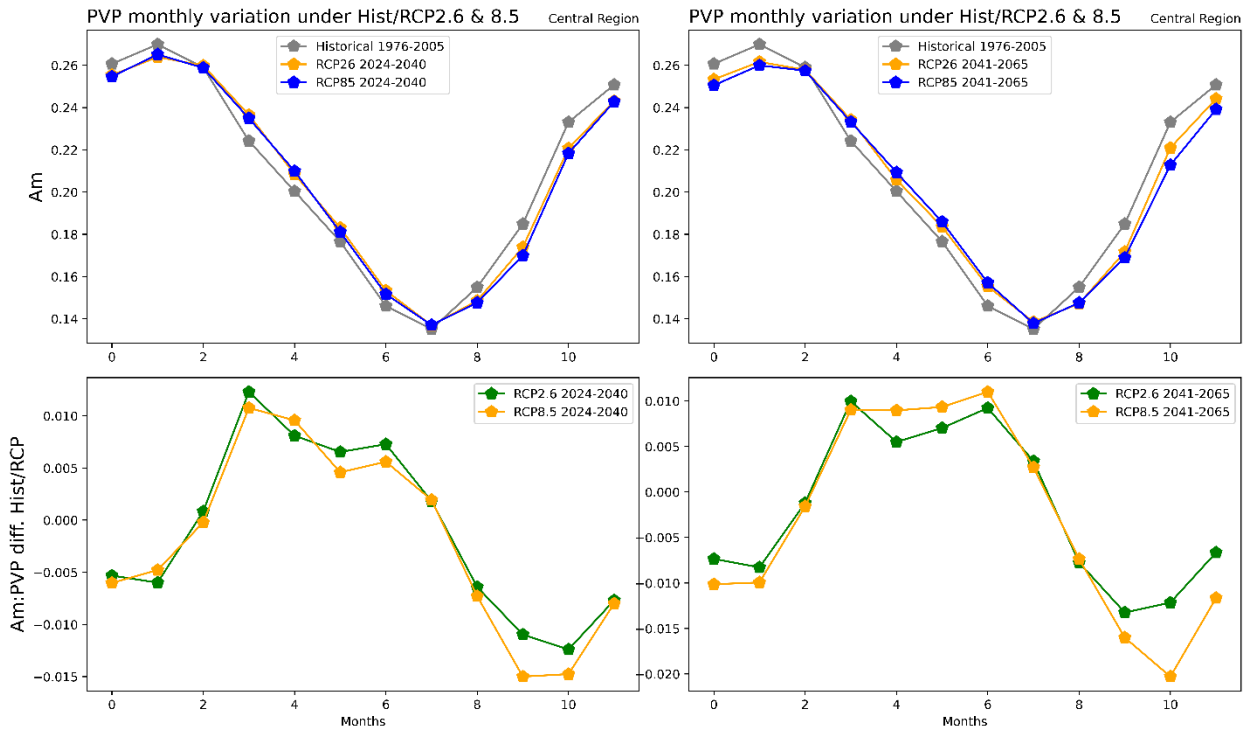
Climatological variation and difference of projected change in PVP from 2024-2065 under RCP2.6 & 8.5 scenarios in relation with Amorphous crystalline cell technology over Plateaux region



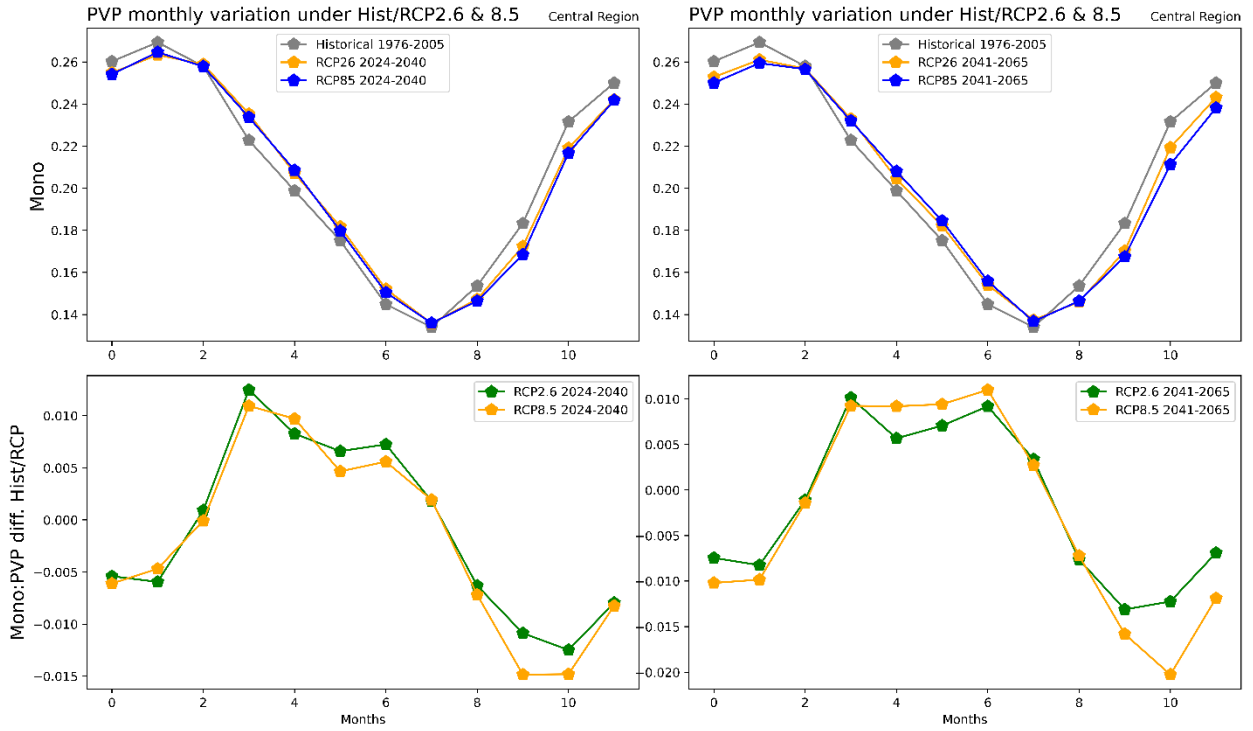
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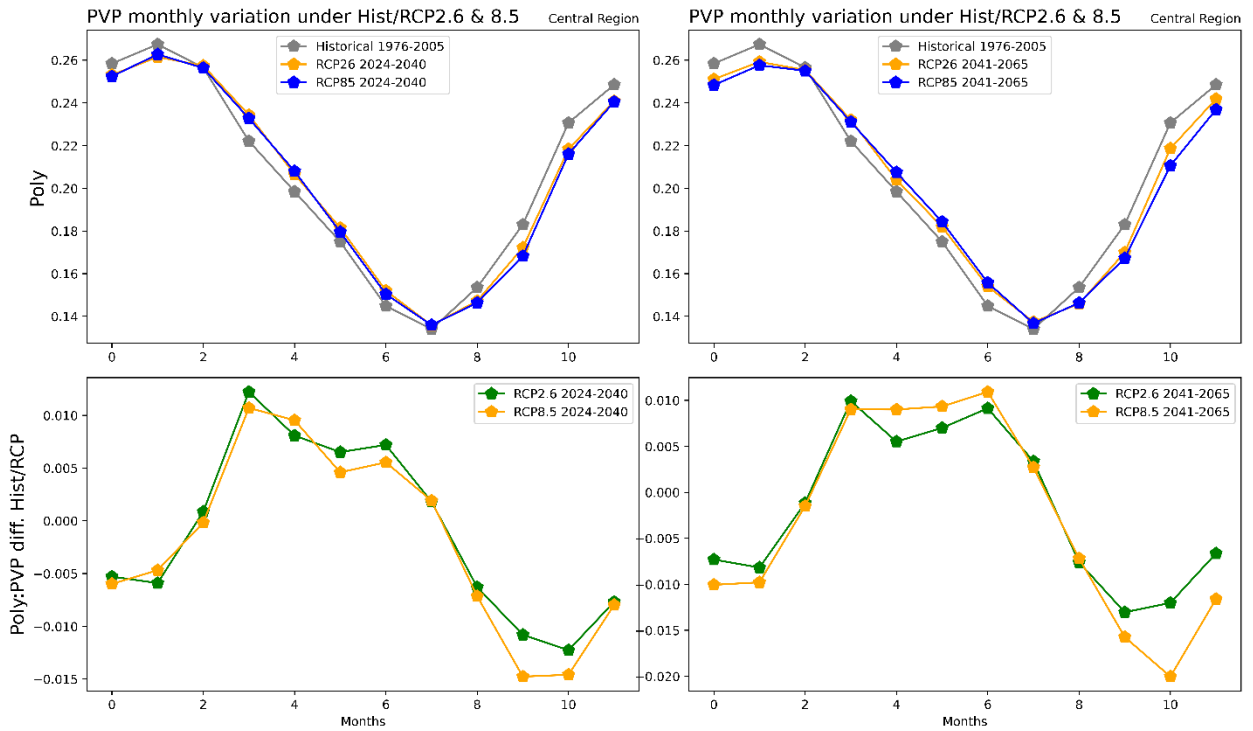
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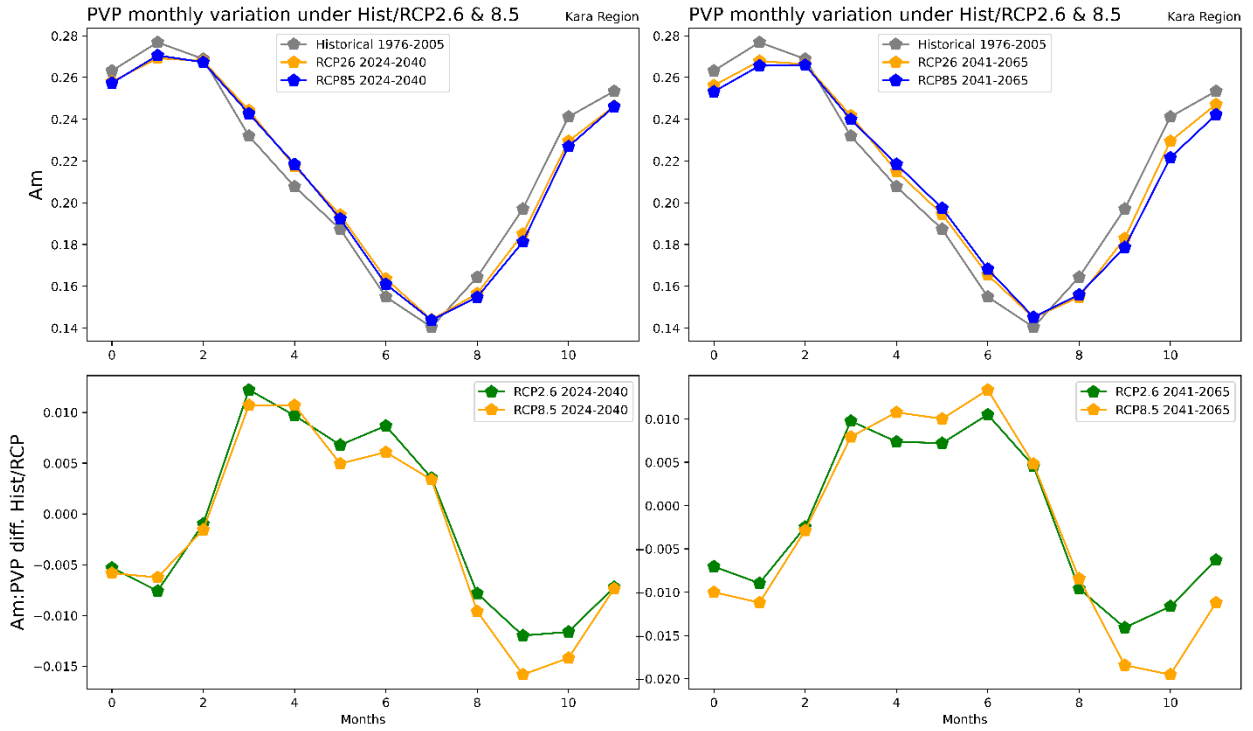
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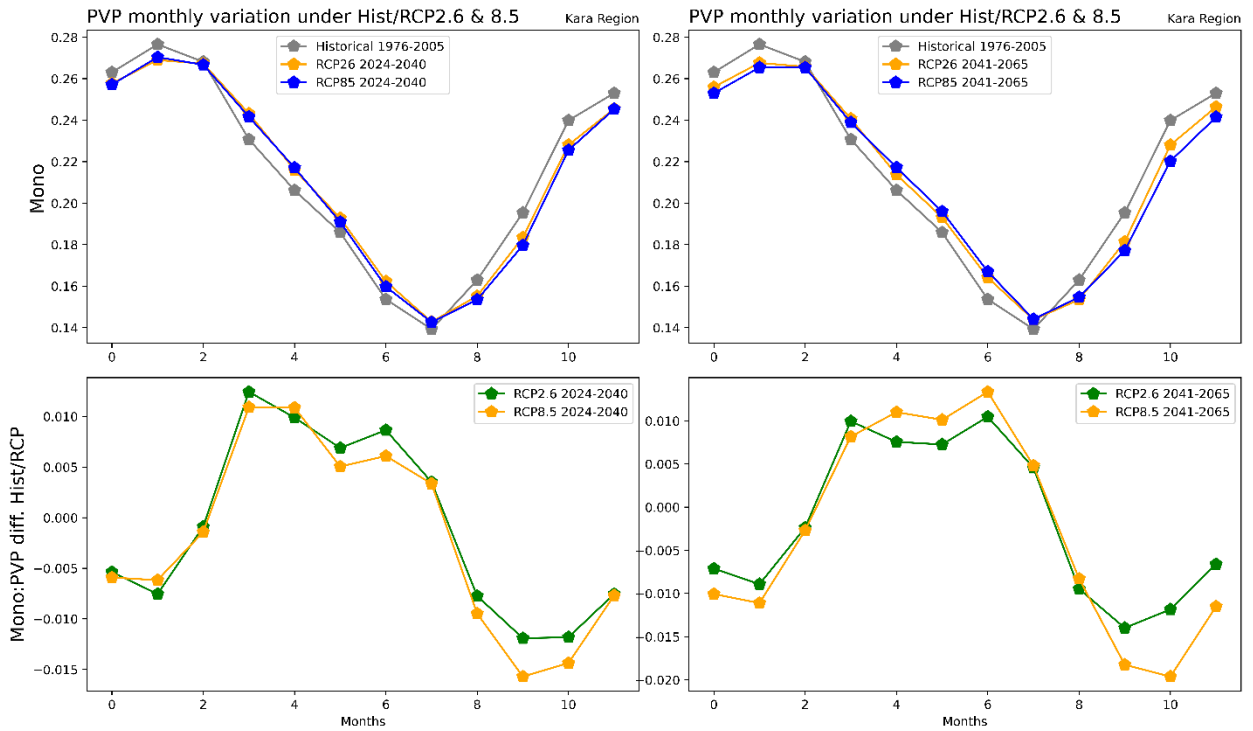
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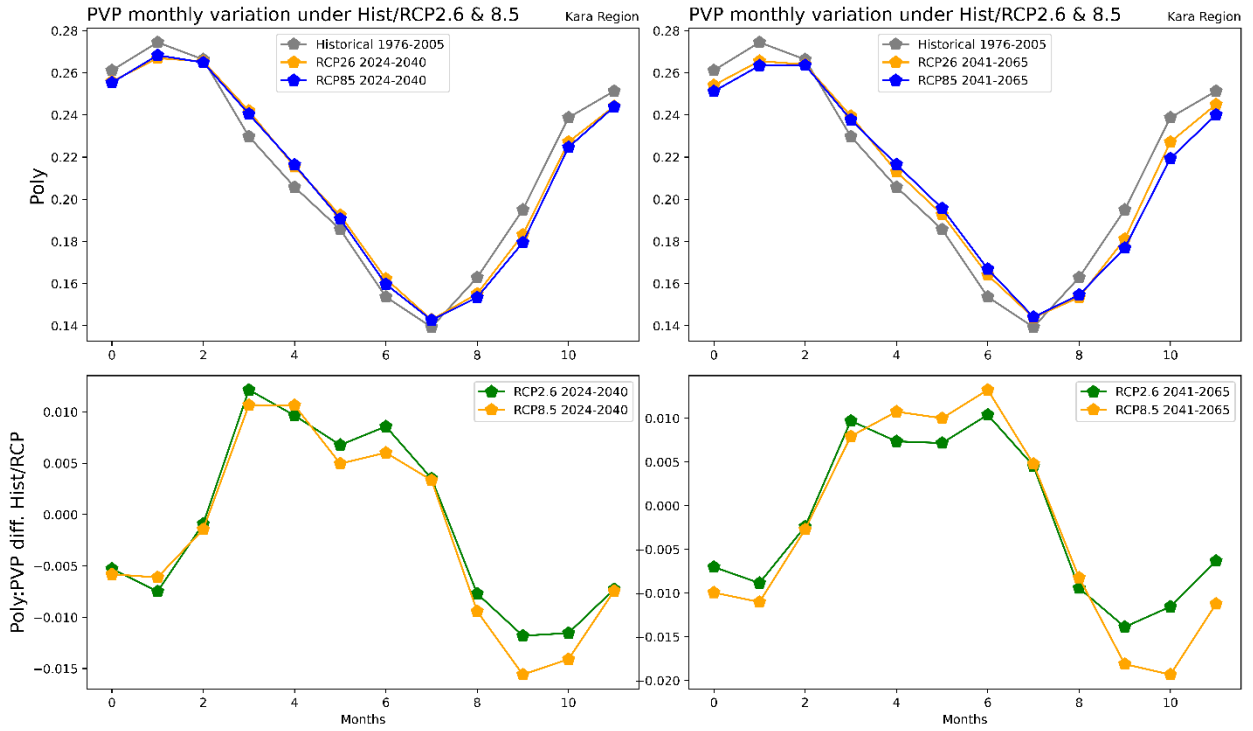
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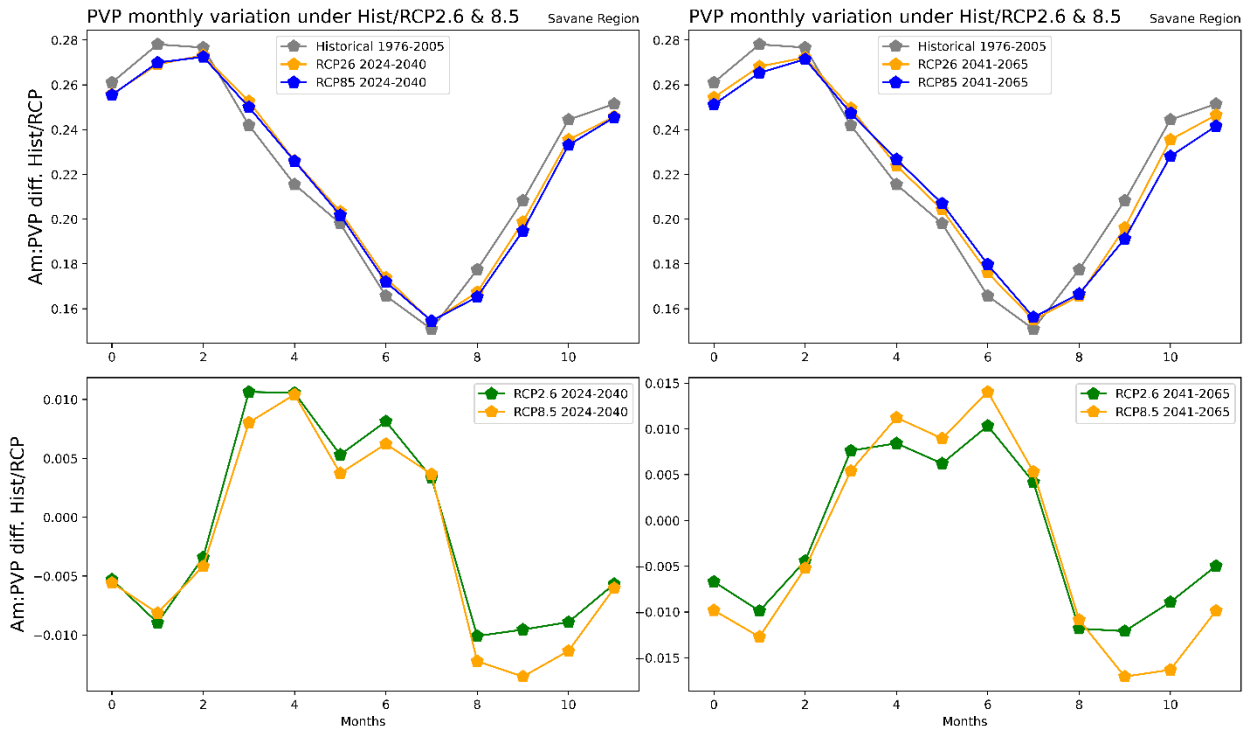
Climatological variation and difference of projected change in PVP from 2024-2065 under RCP2.6 & 8.5 scenarios in relation with Amorphous crystalline cell technology over Kara region



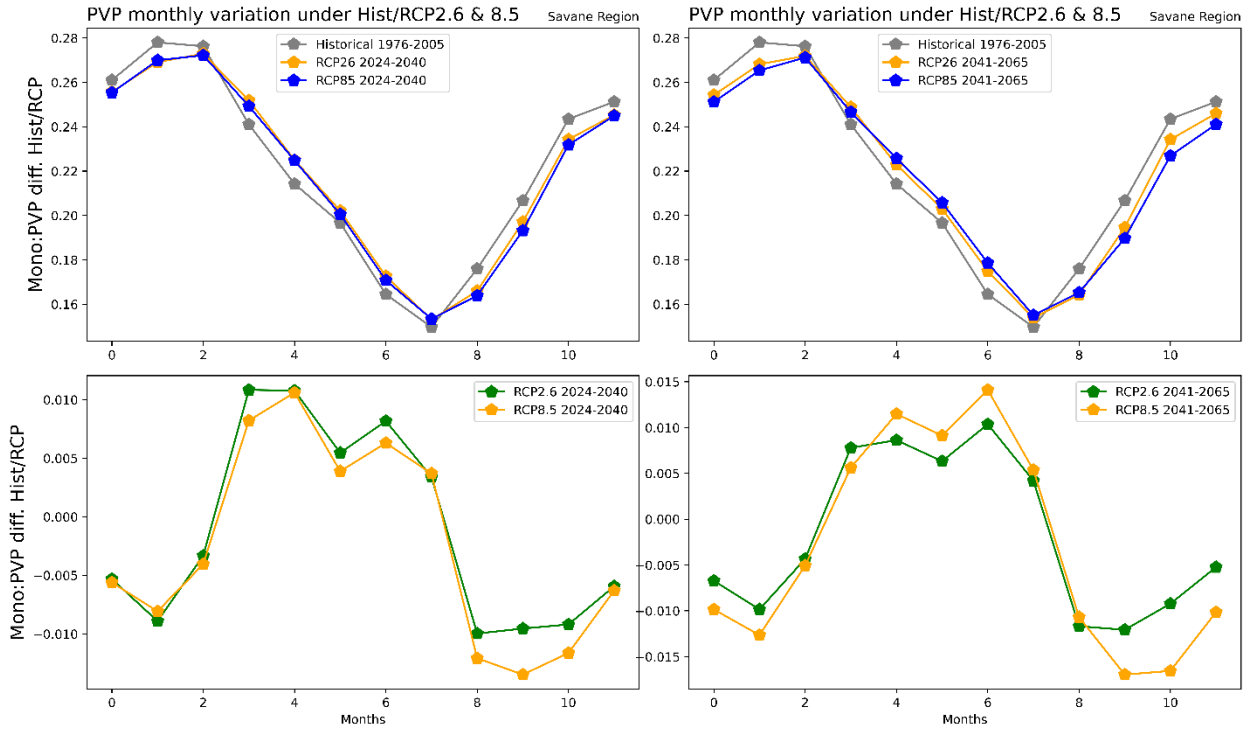
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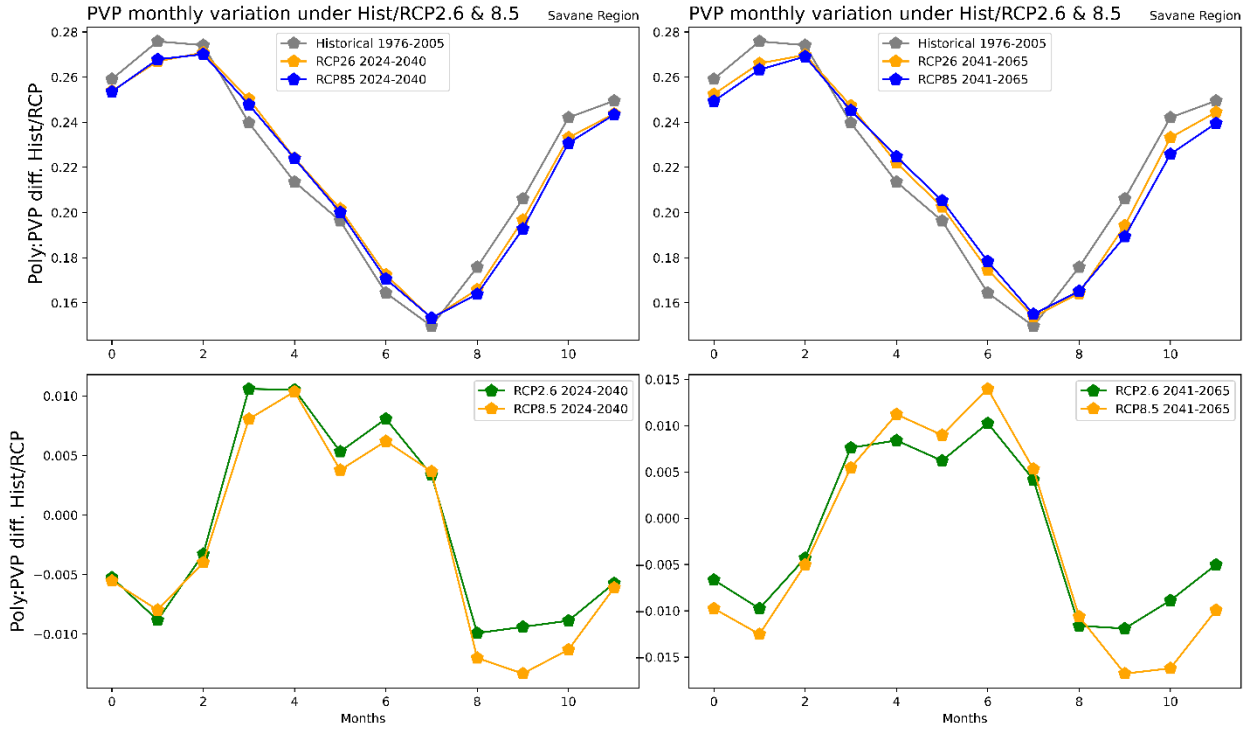
Climatological variation and difference of projected change in PVP from 2024-2065 under RCP2.6 & 8.5 scenarios in relation with Poly crystalline cell technology over Kara region



Climatological variation and difference of projected change in PVP from 2024-2065 under RCP2.6 & 8.5 scenarios in relation with Poly crystalline cell technology over Savannah region

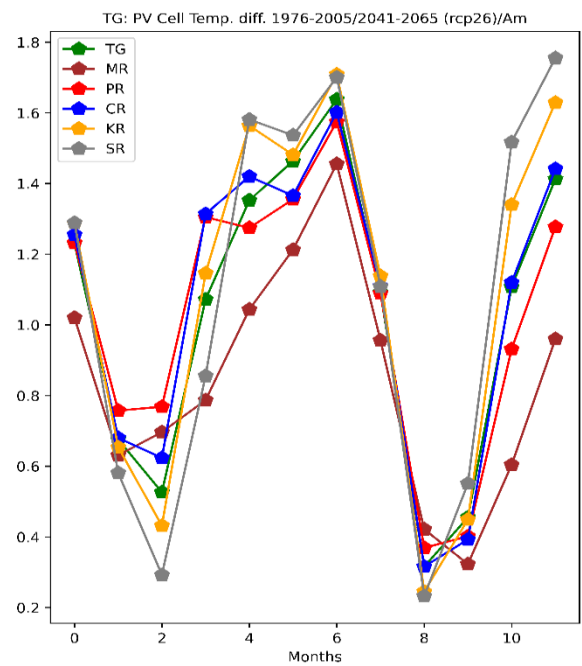
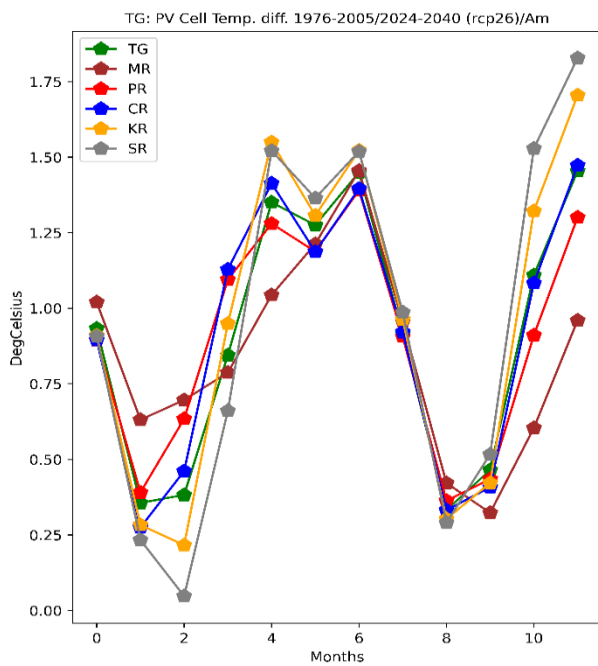


Climatological variation and difference of projected change in PVP from 2024-2065 under RCP2.6 & 8.5 scenarios in relation with Poly crystalline cell technology over Savannah region

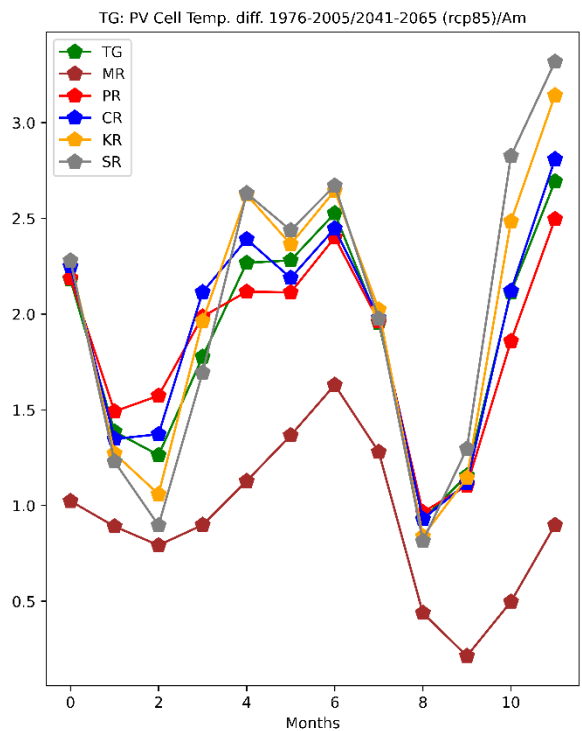
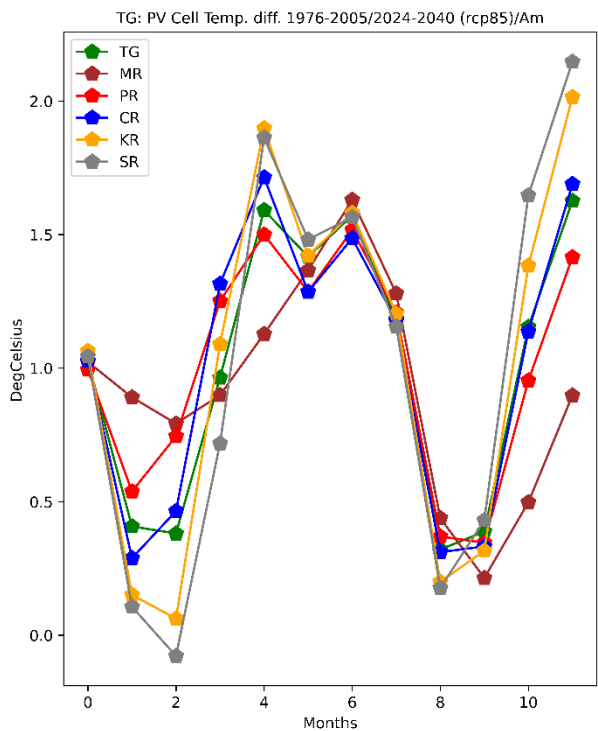


Climatological variation and difference of projected change in PVP from 2024-2065 under RCP2.6 & 8.5 scenarios in relation with Poly crystalline cell technology over Savannah region

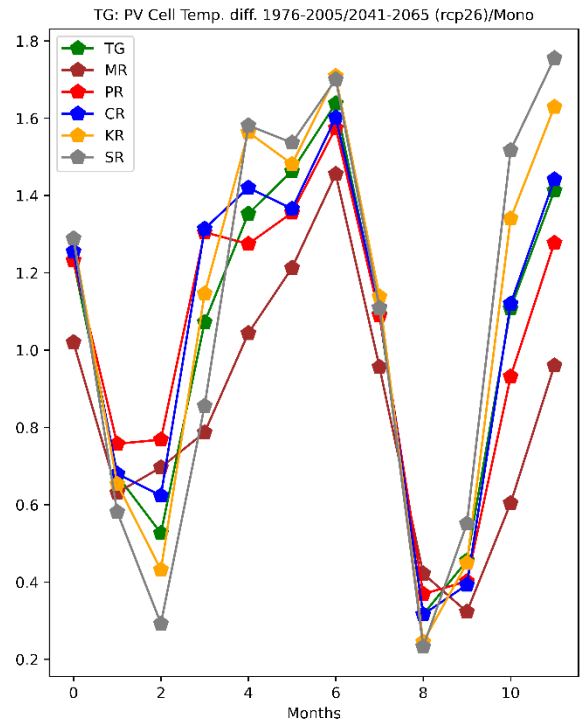
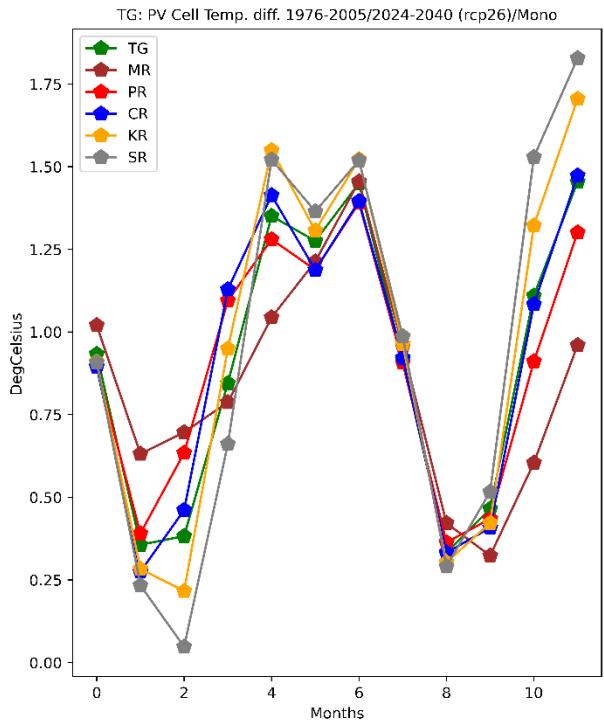
Appendix 4: PVct variation figures superposed



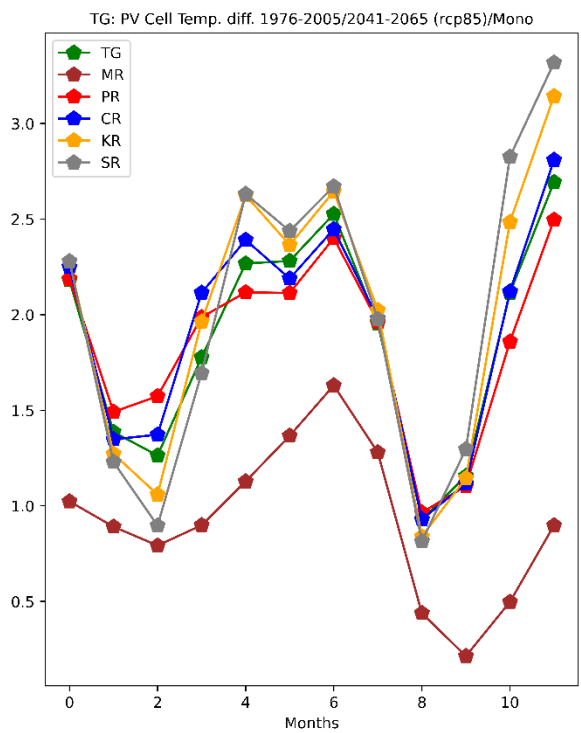
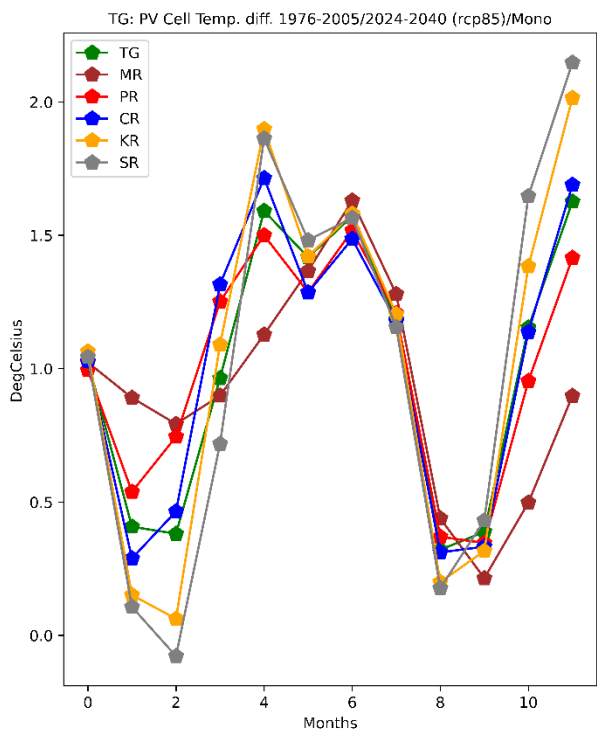
PVct variation across the administrative regions and over the country under a-Si and RCP2.6 superposed during near & middle futures



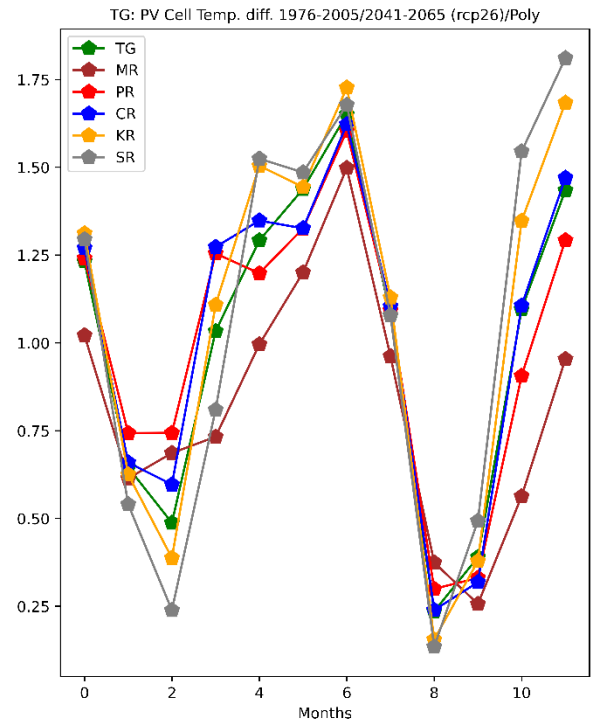
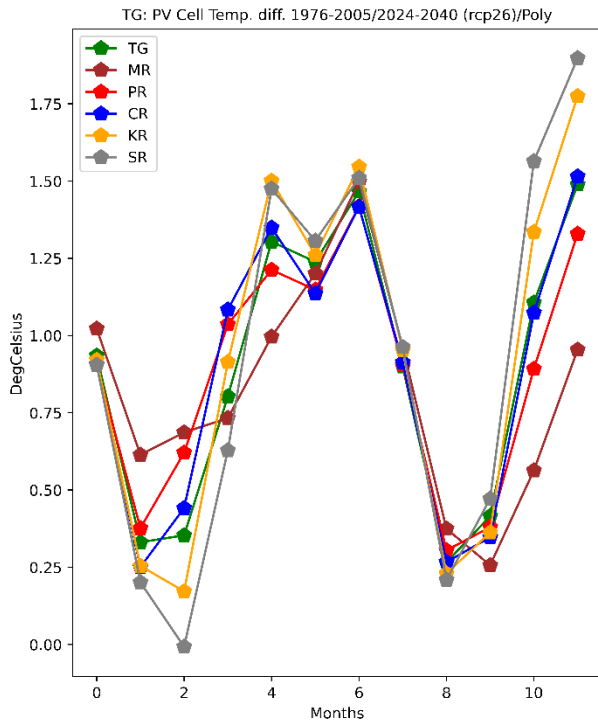
PVct variation across the administrative regions and over the country under a-Si and RCP2.6 superposed during near & middle futures



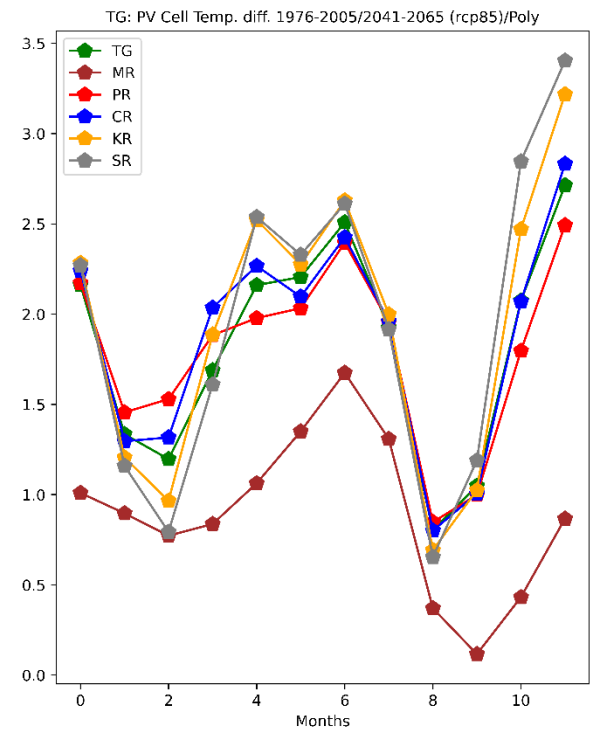
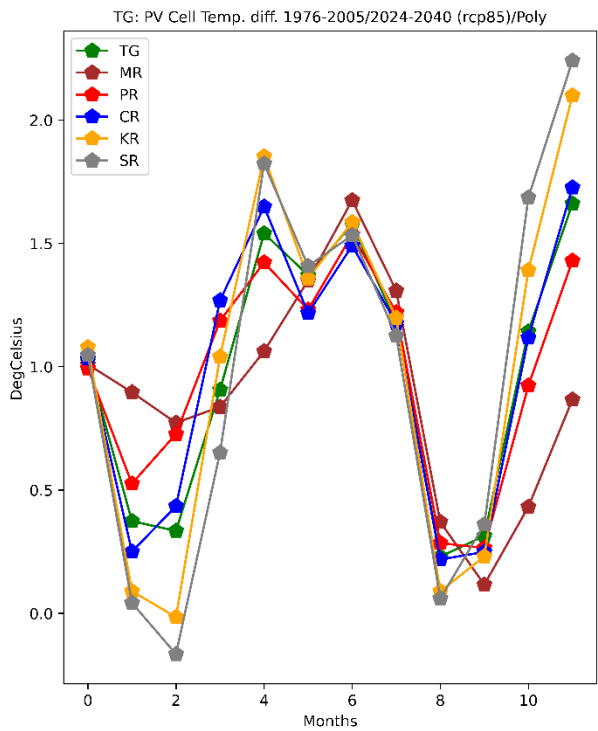
PVct variation across the administrative regions and over the country under Mono-Si and RCP2.6 superposed during near & middle futures



PVct variation across the administrative regions and over the country under Mono-Si and RCP8.5 superposed during near & middle futures

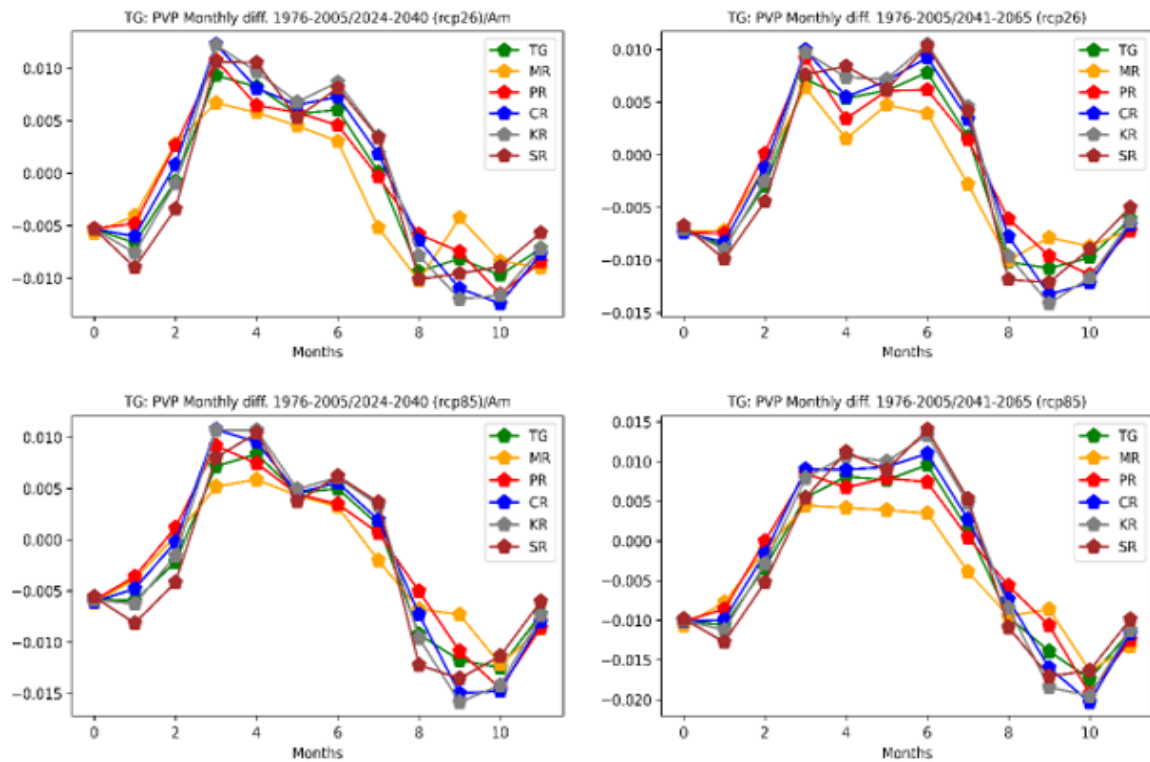


PVct variation across the administrative regions and over the country under Poly-Si and RCP2.6 superposed during near & middle futures

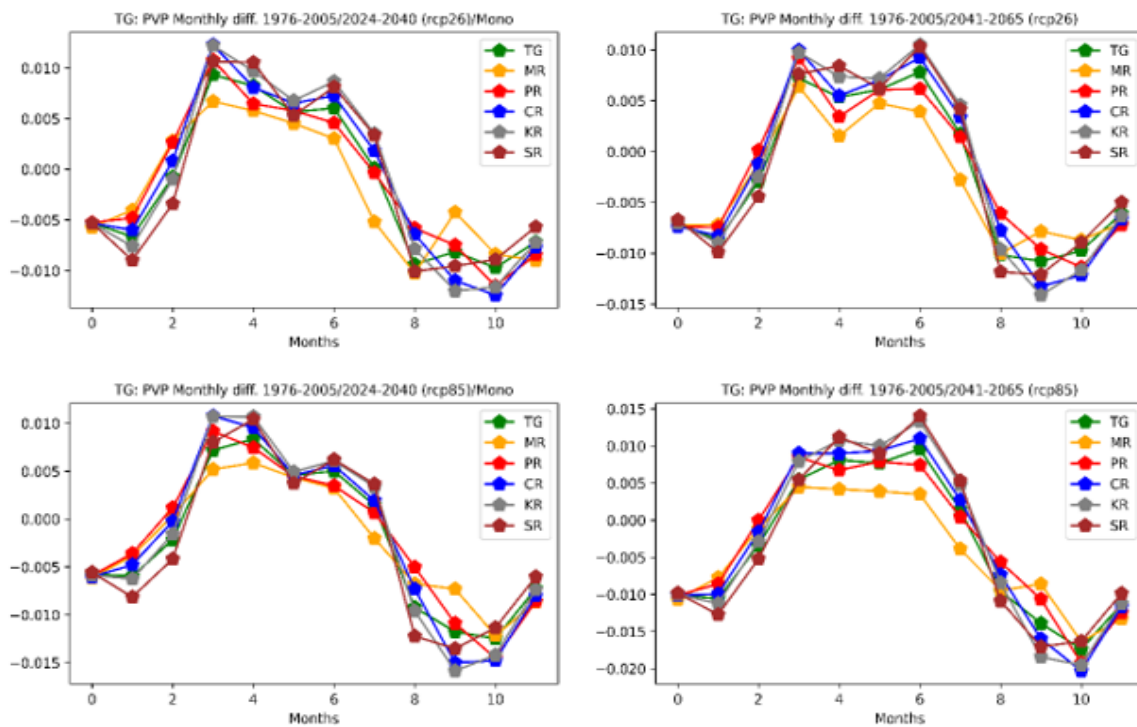


PVct variation across the administrative regions and over the country under Mono-Si and RCP8.5 superposed during near & middle futures

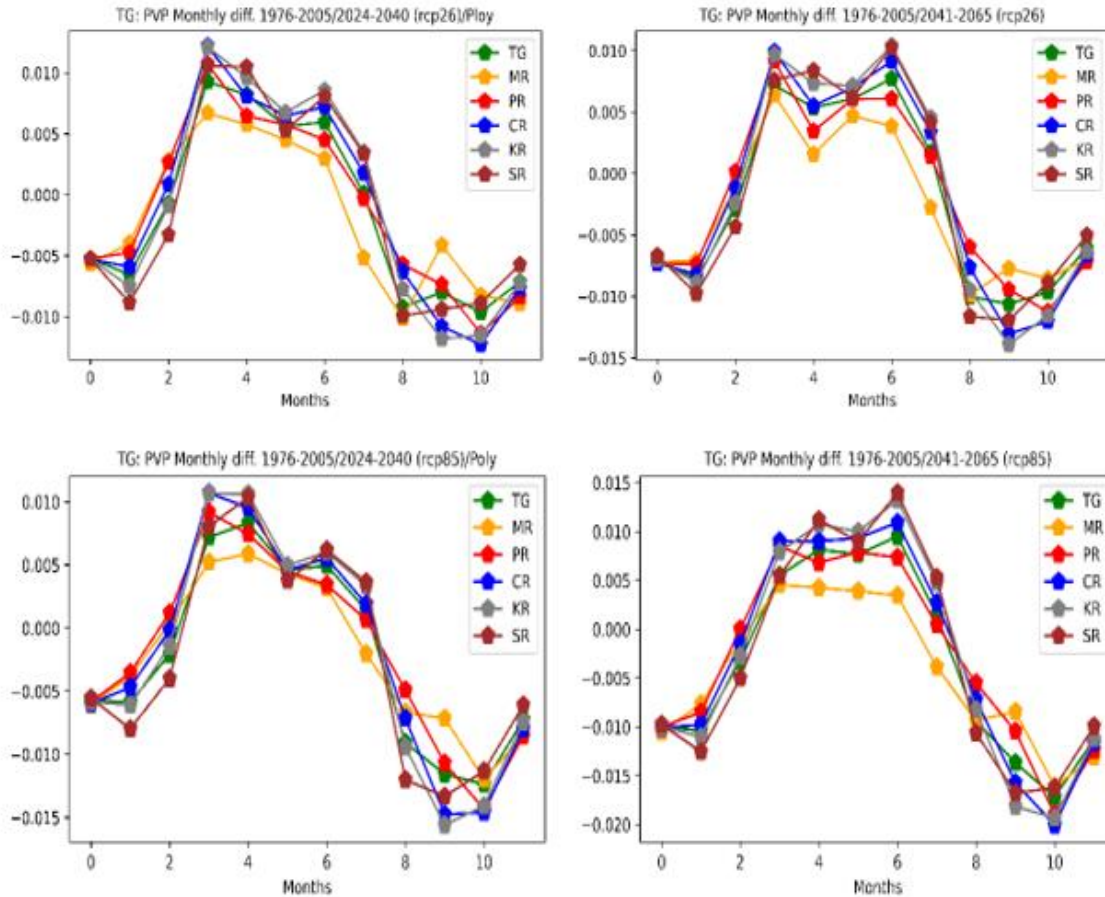
Appendix 5: PVP variation figures superposed



PVP variation across the administrative regions and over the country under a-Si and RCP2.6 & 8.5 superposed during near & middle futures



PVP variation across the administrative regions and over the country under Mono-Si and RCP2.6 & 8.5 superposed during near & middle futures



PVP variation across the administrative regions and over the country under Poly-Si and RCP2.6 & 8.5 superposed during near & middle futures

Appendix 6: Summary of PVct and PVP variation across the administrative regions and over the country under PV cell technology and RCP2.6 & 8.5 superposed during near & middle future

a-Si									
Domains	RCP2.6		RCP8.5		Domains	RCP2.6		RCP8.5	
	PVct variation 2024-2040	PVct variation 2041-2065	PVct variation 2024-2040	PVct variation 2041-2065		PVP variation 2024-2040	PVP variation 2041-2065	PVP variation 2024-2040	PVP variation 2041-2065
Togo	0.9055 84505	1.0284 47938	1.0022 77205	1.8771 16358	Togo	- 0.001 4736	- 0.002 267	- 0.002 3408	- 0.003 6558
Maritime	0.8424 39808	0.8424 39808	0.9211 45295	0.9211 45295	Maritime	- 0.001 9902	- 0.002 9462	- 0.002 3253	- 0.004 5917
Plateaux	0.8988 10391	1.0278 99743	1.0100 68893	1.8543 40545	Plateaux	- 0.001 1155	- 0.001 8851	- 0.001 8405	- 0.002 975
Central	0.9142 45288	1.0531 61622	1.0188 69714	1.9219 71322	Central	- 0.000 9974	- 0.001 7909	- 0.001 9736	- 0.002 9892

Kara	0.9540 9059	1.0895 13945	1.0318 29508	1.9864 93583		Kara	- 0.000 9742	- 0.001 7322	- 0.002 0757	- 0.002 9064
Savannah	0.9501 43339	1.0833 05832	1.0210 89872	2.0055 2082		Savannah	- 0.001 1586	- 0.001 8454	- 0.002 4154	- 0.003 083
Mono Si										
Domains	RCP2.6		RCP8.5			Domains	RCP2.6		RCP8.5	
PVct variation	2024- 2040	2041- 2065	2024- 2040	2041- 2065		PVP variation	2024- 2040	2041- 2065	2024- 2040	2041- 2065
Togo	0.8852 93003	1.0083 90427	0.9753 01102	1.8230 80692		Togo	- 0.001 4556	- 0.002 2467	- 0.002 3097	- 0.003 5974
Maritime	0.8295 57424	0.8295 57424	0.8978 18246	0.8978 18246		Maritime	- 0.001 9719	- 0.002 9197	- 0.002 2922	- 0.004 5324
Plateaux	0.8781 19136	1.0099 89418	0.9755 93579	1.7952 66158		Plateaux	- 0.001 0996	- 0.001 8698	- 0.001 8034	- 0.002 9143
Central	0.8887 41807	1.0314 85246	0.9819 25969	1.8558 62612		Central	- 0.000 9788	- 0.001 7744	- 0.001 9342	- 0.002 924
Kara	0.9319 83639	1.0690 70491	1.0003 76712	1.9259 37017		Kara	- 0.000 9612	- 0.001 7191	- 0.002 0437	- 0.002 851
Savannah	0.9273 51463	1.0591 9281	0.9949 69043	1.9454 66525		Savannah	- 0.001 1432	- 0.001 827	- 0.002 3896	- 0.003 0281
Poly Si										
Domains	RCP2.6		RCP8.5			Domains	RCP2.6		RCP8.5	
PVct variation	2024- 2040	2041- 2065	2024- 2040	2041- 2065		PVP variation	2024- 2040	2041- 2065	2024- 2040	2041- 2065
Togo	0.8837 08632	1.0009 82919	0.9703 94782	1.8178 13539		Togo	- 0.001 4442	- 0.002 2251	- 0.002 293	- 0.003 5744
Maritime	0.8214 76307	0.8214 76307	0.8909 41306	0.8909 41306		Maritime	- 0.001 9571	- 0.002 897	- 0.002 2789	- 0.004 5008
Plateaux	0.8772 57333	1.0025 04038	0.9783 39189	1.7942 67008		Plateaux	- 0.001 0898	- 0.001 8489	- 0.001 7982	- 0.002 8993
Central	0.8914 77898	1.0277 50973	0.9854 66635	1.8616 581		Central	- 0.000 9717	- 0.001 7562	- 0.001 9284	- 0.002 9138

Kara	0.9349 49245	1.0667 52113	0.9995 71476	1.9303 64923		Kara	- 0.000 9532	- 0.001 7018	- 0.002 0305	- 0.002 8366
Savannah	0.9267 16012	1.0527 06244	0.9839 48232	1.9428 58853		Savannah	- 0.001 1313	- 0.001 8049	- 0.002 3613	- 0.003 0041