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Economic and Environmental Challenges of Energy Transition Within the Economic Community of West African States

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Dedication

I dedicate this work to the Almighty God, whose boundless grace and gift of good health have sustained me until now.

To my dear family, whose unwavering support and heartfelt encouragement have been a constant source of strength.

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SIGLES AND ACRONYMS

AFD	French Development Agency/Agence Française De Développement
AfDB	African Development Bank
AFREC	Africa Energy Commission
AFRETRAP	Africa Energy Transition Program
CEET	Togolese Electricity Company
CGE	Computable General Equilibrium
COP	Conference Of the Parties
CSP	Concentrating Solar-Thermal Power
DEA	Development Envelopment Analysis
ECOWAS	Economic Community of West African States
ECREEE	ECOWAS Centre For Renewable Energy and Energy Efficiency
ECT	Error-Correction Term
EE	Energy Efficiency
EEEP	Ecowas Energy Efficiency Policy
EKC	Environmental Kuznets Curve
EREP	Ecowas Renewable Energy Policy
EROI	Energy Return On Investment
ES	Energy Security
GHG	Greenhouse Gas
GHI	Global Horizontal Irradiation
GJAM	Green Jobs Assessment Modelling
HP	Hydropower
IAM	Integrated Assessment Models
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LPG	Liquefied Petroleum Gas
MLP	Multi-Level Perspectives
NDC	Nationally Determined Contributions
NES	National Electrification Strategy

NRE	Non-Renewable Energy
NREEP	National Renewable Energy and Energy Efficiency Policy
OECD	Organisation For Economic Cooperation and Development
PCA	Principal Component Analysis
PI	Physical Infrastructure
PV	Hybrid Photovoltaic
R&D	Research And Development
RE	Renewable Energy
RES	Renewable Energy Sources
ROGEP	Regional Off-Grid Electrification Project
RREEEP	Regional Renewable Energy and Energy Efficiency Policy
SAM	Social Accounting Matrix
SBM	Slack-Based Measures
SDGs	Sustainable Development Goals
SDNI	Direct Normal Irradiance
SE4LL	Sustainable Energy For All
SHS	Solar Home Systems
SP	Solar Photovoltaic
TEP	Techno-Economic Paradigm
TFC	Total Final Consumption
TPB	Theory Of Planned Behavior
UNCTAD	United Nations Trade and Development
UNFCCC	United Nations Framework Convention on Climate Change
WAPP	West African Power Pool
WDI	World Development Indicators

ABSTRACT

The energy transition is pivotal for tackling energy insecurity, poverty, and climate change, yet its economic, energy security (ES), and energy efficiency (EE) impacts remain underexplored in developing regions like ECOWAS. This dissertation uses a multidimensional approach to assess renewable energy (RE) adoption, energy efficiency investments, and macroeconomic energy policies in Togo and ECOWAS, employing dynamic DEA, ARDL models, and a dynamic CGE model on data from 2000-2021. Results show low average EE (0.58) in ECOWAS, but RE use, especially hydropower, solar PV, and biogas, enhances ES and EE long-term. Cabo Verde leads in EE, while Togo lags with 0.36, highlighting the need for targeted policies. In Togo's Centrale region, household data reveal that RE adoption boosts both monetary and non-monetary EE investments, influenced by life satisfaction, environmental attitudes, and socio-demographics. Incentives promoting joint RE and EE adoption can accelerate net-zero-energy buildings and sustainability. At the macro level, CGE analysis using Togo's 2018 SAM shows that R&D investment yields high returns through innovation and productivity gains, while infrastructure investment boosts energy reliability and industrial output, albeit with higher capital needs. Combined strategies drive GDP growth, government revenues, and household savings, though disparities remain in agriculture and informal sectors. Overall, integrated micro and macro policies promoting RE, EE, and strategic investment are key to strengthening ES, economic resilience, and sustainability in Togo and ECOWAS.

Keywords

Energy transition; Energy policy; Energy security; Energy efficiency; Renewable energy.

Résumé

La transition énergétique est essentielle pour lutter contre l'insécurité énergétique, la pauvreté et le changement climatique. Cependant, ses impacts économiques, en matière de sécurité énergétique (SE) et d'efficacité énergétique (EE), restent peu explorés dans les régions en développement telles que la CEDEAO. Cette thèse adopte une approche multidimensionnelle pour évaluer l'adoption des énergies renouvelables (ER), les investissements en efficacité énergétique, ainsi que les politiques macroéconomiques de l'énergie au Togo et dans la CEDEAO, en mobilisant des modèles DEA dynamique, ARDL et un modèle d'équilibre général calculable (MEGC) dynamique, sur la base de données couvrant la période 2000-2021. Les résultats révèlent une EE moyenne faible (0,58) dans la CEDEAO. Toutefois, l’utilisation des ER, en particulier l’hydroélectricité, le solaire photovoltaïque et le biogaz, améliore durablement la SE et l’EE. Le Cap-Vert se distingue par sa performance en matière d’EE, tandis que le Togo enregistre un score inférieur (0,36), soulignant la nécessité de politiques ciblées. Dans la région Centrale du Togo, les données ménagères indiquent que l’adoption des ER favorise les investissements en EE, tant sur les plans monétaires que non monétaires, influencés par la satisfaction de vie, les attitudes environnementales et les caractéristiques socio-démographiques. Des incitations à l’adoption conjointe des ER et de l’EE pourraient accélérer l’émergence de bâtiments à énergie nette zéro et la durabilité. À l’échelle macroéconomique, l’analyse MEGC fondée sur la matrice de comptabilité sociale (MCS) du Togo de 2018 montre que l’investissement en recherche et développement (R&D) génère des rendements élevés via l’innovation et les gains de productivité, tandis que l’investissement dans les infrastructures améliore la fiabilité énergétique et la production industrielle, bien qu’il nécessite davantage de capitaux. Les stratégies combinées stimulent la croissance du PIB, les recettes publiques et l’épargne des ménages, même si des disparités persistent dans les secteurs agricole et informel. En somme, des politiques intégrées aux niveaux micro et macro, favorisant les ER, l’EE et les investissements stratégiques, sont cruciales pour renforcer la SE, la résilience économique et la durabilité au Togo et dans l’espace CEDEAO.

Mots clés :

Transition énergétique ; Politiques énergétiques ; sécurité énergétique ; efficience énergétique ; énergies renouvelables.

GENERAL INTRODUCTION

Research background

The importance of access to electricity is becoming a matter of course nowadays. This importance relies on mutations electric energy mutations induced in all economic ecosystems and materialized by Goal 7 of the Sustainable Development Goals (SDGs), which aims to ensure access to reliable and modern energy services for all at an affordable cost by 2030. It also appeared in the African Union Agenda 2050, whose objective on the energy front is to unify an African energy system. The importance of energy in developing countries is also apparent in the first objective of the African Development Bank, which is to light up and power Africa.

Energy is essential for almost all human activities. This resource is virtually irreplaceable in populations' social and economic lives worldwide. Van de Walle et al. (2017) show that access to electricity increases household consumption and, as a result, their well-being. Access to electricity simultaneously enables and improves the delivery of social and business services (e.g., schools, markets, and water pumps) while improving the productivity of agricultural activities (Kirubi et al., 2009). Therefore, it has been identified as a production factor, as well as capital, labor, and land (Kümmel, 1989; Stern, 1997). Electricity participates in the short, medium, and long term as a powerful stimulus to development, acting positively on productivity, income, and through trickle-down to household welfare (Kirubi et al., 2009; van Gevelt, 2014; van de Walle et al., 2017; Sarkodie & Adams, 2020). This factor in industrial production, which consists of work performance and information processing, in terms of which the production factors and the output can be defined and aggregated, is a fundamental factor and impacts production in a transition economy (Kassim & Isik, 2020; Kümmel, 1982).

Although energy is economically important, Sub-Saharan Africa is still characterized by the lowest proportion of energy access. Indeed, in the region, only over two-fifths of the population has access to electricity (AFD, 2019). In addition, although access has slowly increased, only 42.8 percent of Africa's population had access to electricity in 2016. More than 600 million people live without electricity in Africa, including more than 80 percent of rural residents. Only two countries in the region, Mauritius and Seychelles, have achieved near-universal coverage. Also, only six countries in sub-Saharan Africa have a household electricity access rate of 75 percent or higher. Nearly two-thirds of the countries in the region have access rates below 50 percent (AFD, 2019).

Africa has a low access rate compared to other regions. Indeed, the rate of access to electricity was 45% in 2017 in sub-Saharan Africa, while it is 90% in South Asia and more than 97% in East Asia and the Pacific in the same year. In addition, we note an ambivalence in Africa within these countries, on the one hand, those with rates of access to electricity above 75%, and others with rates below 25%. In terms of electrification, Algeria is the leading promoter in Africa. According to the World Bank, the country is covered at 100%. It is the only one in this case, even if Egypt and Tunisia (99.8%), or Libya (99.4%) are also close to perfection. Most of the continent is half covered, for instance, in Senegal (61%), Nigeria (57.7%), Namibia (49.6%), and Sudan (44.9%). On the other hand, many African countries still have low electrification levels. This is the case in Mali (23.7%), Somalia (19.1%), Madagascar (16.8%), and the Democratic Republic of Congo (13.5%). Liberia (9.1%), Chad (8%), Burundi (7%), and South Sudan (4.5%) are the countries with the lowest electrification rates in Africa.

In response to this lower access, households still use biomass and firewood as a source of heating and cooking energy, making universal access (SDG7) an overarching goal for African countries. Anthropogenic activities are the main source of Greenhouse gas emissions (IPCC, 2012, 2022) and constitute the primary factor of global warming. In 2017, African countries contributed 3.9% of the global total emissions from fossil fuel use (IRENA, 2021). This share confirms that the African continent constitutes a less polluter, but its energy sector represents 39% of all its anthropogenic GHG emissions and generates mostly CO2 (IRENA, 2021), which accounts for the largest share of the continent's global GHG emissions. This situation is the consequence of the growth of per capita energy consumption coupled with the predominance of coal in the African electricity mix.

In terms of sectoral contributions in Africa, the electricity and heat sectors are followed by transport (29%) and industry (13%). The first two sectors, mostly powered by coal fuel in Africa, emitted nearly 70% of total CO2 emissions in 2019 (IRENA, 2021). Commercial and public service, and agriculture jointly are less polluting in the African economies. As energy sources, oil and coal are mostly responsible for CO2 emissions in Africa. There is a consensus that these emissions will continuously increase in the future due to the growing electricity demand (IRENA, 2021). This increasing electricity demand is a consequence of Africa's growing demographics and economies, coupled with high rates of urbanization. In terms of projections, more than half of the world's population growth by 2050 is expected to take place in Sub-Saharan Africa. Therefore, the electricity demand will increase, and without a rapid and deep transformation of energy systems, the climate and environmental threats will pose several challenges to Africa's development (IPCC, 2022; IRENA, 2021).

Sub-Saharan Africa thus appears to have tremendous energy reserves that can ensure self-sufficiency in terms of access to electricity. However, there is a contrast between a region rich in energy resources and a relatively poor performance in terms of supply of and access to electricity. Indeed, the African continent is home to excellent hydrocarbon deposits. More than half of the quantities discovered in recent years have been in Africa. Africa holds about 10% of the world's oil reserves, of which about 30% is in Nigeria. Oil reserves in Africa are equivalent to about 40 years of production (African Development Bank (AfDB), 2018). Coal is also an abundant energy resource in sub-Saharan Africa, mainly in South Africa and Zimbabwe. South Africa holds the ranking with an annual production of about 250 million tons (AfDB, 2018). Natural gas is located mainly in Central and West Africa and is used mainly for industrial purposes, with large deposits in Tanzania and Mozambique. Sub-Saharan Africa has a strong presence of large-scale rivers such as the Congo River, which has favoured the implementation of the "Renaissance" dam project in Ethiopia and the "Inga III" dam project in Congo. On the other hand, the energy supply on the continent remains the lowest compared to other regions. International Energy Agency (IEA), (2021) reported that Africa's total energy supply in 2019 was 35.88 Exajoules, while it was 224.789-, 142.49 Exajoules in the OECD and China, respectively, in the same year. The world's total energy supply during 2019 was 606.489, representing 86% of non-renewable energy sources (coal, oil, natural gas, and nuclear) and 12% of renewable energy sources (Hydro, Biofuels, and waste).

Therefore, energy transition is identified as a substantial, cost-effective opportunity to rapidly reduce emissions (Dell'Anna, 2020; Gafa et al., 2022; Egbendewe-Mondzozo et al., 2015; Egbendewe-Mondzozo, 2014). This assertion comes under the consequence that the use of fossil fuels may be insufficient and unsustainable to support growing economies. Thus, each stage of economic development has been accompanied by the characteristics of energy transition from one major energy source to another. The energy transition is necessarily contextualized within a broader economic transition to a low-carbon economy. Any country's economic growth and development are supported by an adequate, reliable, and efficient supply of energy (Augutis, et al., 2015; Malla, 2013). The relationship between renewable energy and sustainable development is said to be positive due to its impact on human development and economic productivity (Owusu & Asumadu-Sarkodie, 2016). These energy sources offer great potential for energy security, social and economic development, energy access, climate change mitigation, and reduced environmental and health impacts. In addition, African potentialities in renewable energy are not negligible. According to IRENA, (2014), West Africa presents 22747-, 103754-, and 40846-Terawatt Hour per year respectively in terms of potentialities of Concentrated Solar Power (CSP), Photovoltaic (PV), and Wind as sources of RE. In addition, Sub-Saharan Africa is also among the sunniest areas in the world with a potential of 5 to 6 kWh/m2/day. A wind potential between 5 and 7 m/s, especially along the coast or in desert areas.

Several programs and projects have therefore been launched to accelerate Africa's energy access and the transition process. Not exhaustively, those initiatives at both continental, regional, and country levels are the Africa Energy Transition Program (AFRETRAP), Energy Transition Program, Energy Efficiency Program, Bioenergy Program, and Oil and Gas Program from Africa Energy Commission (AFREC), the high 5s for the African Development Bank with a line of the energy issue. Those programs are geared towards transforming the African energy market to higher efficiency lighting and electrical appliances with a strategic integrated energy policy approach at the continental level to significantly reduce the continent's final energy demand and provide increased electricity access, competitiveness, energy security, and economic development. Moreover, in most programs, the African priority is renewable energy production to benefit from the potential relationship between their adoption, energy efficiency measures, and socio-economic aspects (Saygin et al., 2015), and climate benefits. Despite these initiatives, the economic challenges of energy transition in ECOWAS Countries remain huge.

Problem statement

Despite the reforms carried out by sub-Saharan African countries, performance in terms of adequate energy access remains the Achilles heel of the region's development (Sarkodie & Adams, 2020). Indeed, the continent's gross domestic product per unit of energy use (GDP/kg of oil equivalent) is the lowest in the continent compared to others. The World Bank reported that the world GDP/kg of oil equivalent was 8.31 in 2015, while 6.44, 7.64, and 5.74 in Sub-Saharan Africa, Africa’s western and central, and Africa’s eastern and southern, respectively (World Bank, 2015). In the same year, in contrast, the Organization for Economic Cooperation and Development (OECD), the European Union, and North America reported, respectively, 10.45, 12.90, and 8.32 as GDP/kg of oil equivalent. In addition, the energy supply is dominated by non-conventional sources whose overexploitation is not only likely to make all social strata and ecosystems vulnerable but is also a source of environmental externalities such as greenhouse gas emissions or climate change (GHG) (Herrera et al., 2018; Dato, 2017). Indeed, although energy is a fundamental production factor that can lead to economic growth and development, it is proving to be one of the main sources of environmental degradation. According to IEA statistics, more than 80% of global energy demand is met using fossil fuels (IEA, 2017). The Intergovernmental Panel on Climate Change (IPCC) reported that CO2 emissions attributable to the use of fossil fuels and industrial processes have contributed more than 78% to the increase in total global greenhouse gas emissions (GHG) between 1970 and 2010 (IPCC, 2014). In addition, these CO2 emissions from energy consumption could increase by 40% by 2030 (IPCC, 2007).

This reinforces the global theoretical and empirical debates on the impacts of energy transition that can be characterized by retrospective and prospective studies (Fleurbaey et al., 2014). In the case of the former, studies have found that development paths are examined from different aspects that include GHG emissions due to differences in, among other things, fuel supply mix, location patterns, economic activity structure, and household demand composition. As a result, the prospective studies have highlighted an interesting and contrasting, but plausible, view of the future in terms of GHG emissions. The argument focuses on the shift from a high-emissions to a low-emissions development pathway, which requires changing the trajectory of GHG-emitting energy systems. Economic theories contribute to the understanding of the energy transition. The classics follow the mechanisms of transformation from both an economic and social perspective. Their concern with historical change provides insight into the energy transition, especially in developing countries. On the other hand, neoclassical economics' suggestions about prices, externalities, and "creative destruction" are relevant and contribute to understanding this transition (Cherp et al., 2018). However, evolutionary economic theory provides more useful insights into the mechanisms that explain innovations, structural change, organizations, economic structure, and institutions. This framework is based on six central evolutionary concepts, namely "diversity," "innovation," "selection environment," "bounded rationality," "path dependence and lock-in," and "coevolution" (van den Bergh & Oosterhuis, 2005). The energy transition is a concept that has been extensively researched in the existing literature and there are now efforts to integrate it into the national energy policies of most countries. Despite its clarity in terms of implications, there is still debate in the literature regarding its desired end state (Bridge et al., 2013). Energy transitions have become a multidisciplinary issue if we consider its theoretical inquiry into the how and why of transitions, the critical attributes, and the determinants of energy transitions.

In comparison, renewable energy sources are more evenly distributed around the world and less traded in the market than fossil fuels. As a result, they reduce energy imports and contribute significantly to the diversification of the energy mix (the share of renewable and non-renewable in the total energy consumption), reducing economic vulnerability to price volatility and creating more opportunities for energy security in many countries. Overall, per capita income and per capita energy consumption are positively correlated, and economic growth is considered the most pre-determined factor for the increase in energy consumption in recent decades with a significant contribution to poverty reduction and job creation that has improved health, education, gender equality, and environmental security (Edenhofer et al., 2011; Kraft & Kraft, 1978). The energy transition process depends on the targets (Prina et al., 2020; Vidal-Amaro et al., 2015), the expected socio-economic impacts (Dell'Anna, 2020), the current energy mix of the country (Haque, 2022), the financial resources, technical challenges, and the households' capacities to adopt renewable energy (Dato, 2017).

The techno-economic paradigm (TEP) concept and the multi-level perspectives (MLP) school of thought of socio-technological systems guide work on low-carbon energy by upgrading and modernizing existing structures to more sustainable structures or industries (Verbong & Geels, 2007). Following these approaches, more modern energy systems can benefit the economy by providing greater energy security. Indeed, these systems minimize losses from production to final use and reduce the risk of untimely breakdowns at the industrial level for better productivity. However, the energy transition in Africa suffers from poor quality infrastructure which exacerbates the challenge of long-distance electricity transmission, often to rural areas. Thus, the energy insecurity associated with this technical challenge in Africa is accompanied by power outages in enterprises. The Sub-Saharan Africa region has the highest percentage (79%) compared to other regions of the world (AFD, 2019). In addition, Africa's energy systems transformation is characterized by the continuity investment in coal fuel. Steckel et al., (2019) showed that several African countries are looking to invest in new coal-fired power plants or already have plants under construction. The consequence of this situation is the increase in non-renewable energy imports and the low share of renewable energy in total energy consumption. In addition, the shortfall in energy security and efficiency due to the clothed nature of energy systems can be seen as a factor in the slow pace of industrialization and development in Africa (Akinyemi et al., 2019; Bellos, 2018).

The term "transition" can be conceptualized as a non-linear change (Rotmans et al., 2001) that undoubtedly involves different actors. Several policy theories developed based on incentive mechanisms attempt to solve the problems of environmental and resource regulation. Although most of the major economic theories elucidate facts and concepts, they do not directly address transition challenges such as path dependence, lock-in, diversification, bounded rationality, and uncertainty (van den Bergh & Oosterhuis, 2005). Therefore, there are still conflicts between mainstream economics and the transition paradigm. Despite this, several economic terminologies are very close to each other, such as new growth, development, structural change, innovation, and transformation. However, the neoclassical economic theory attempts to explain the energy transition (Cherp et al., 2018) with the central assumption that agents such as households, firms, and government agencies act consistently to maximize a given utility or profit function, and the optimum may depend on their perception and capacities.

Households' investment in energy efficiency refers to monetary or financial (efficiency investments) and non-monetary (curtailments) investments required to reduce overall energy consumption. The former is facing financial challenges that fall into two categories. One is the supply side, and the other is the demand side. On the supply side, the main financial challenge lies in the difficulty of mobilizing investment resources. Indeed, implementing electrification projects requires vast financing well before the start of energy production, while most Sub-Saharan African countries are experiencing severe budgetary constraints. In many African countries, powering a refrigerator for a year costs more than 10% of GDP per capita, and much more for most households, given income inequality (AFD, 2019). The cost of electricity consumption for a refrigerator for a few sub-Saharan African countries compared to developed countries shows that Liberia, Sierra Leone, and Togo have the highest costs as a percentage of GDP while developed countries such as Australia, the UK, or the US have relatively low costs. The latter refers to non-monetary investments involving changes in behavior such as scheduling efforts, turning off lights, cutting down on heating or air conditioning, and switching off standby mode. The two investments monetary and, non-monetary by the government, and households seek to improve energy efficiency in the context of uncertainty (Dato, 2017).

The current share of renewable energy in total energy consumption (Haque, 2022; Yakub et al., 2022; Prina et al., 2020; Vidal-Amaro et al., 2015) and the priority and quality of institutions (Lu et al., 2021) may also be factors that affect the energy transition. Despite several programs and projects in the context of Africa in line with the energy transition, the lockdowns and associated economic crisis related to the Covid-19 pandemic and political crisis have led to enormous difficulties in the energy sector across Africa, especially in efforts to improve access to modern energy services, a deterioration in the affordability of energy for the most vulnerable households, and businesses, and delays in completing and launching critical infrastructure projects (IEA, 2022). The subsequent commodity price surge has worsened matters for importing countries. Following the above threats of the African energy transition, it urges to highlight the economic challenges of this process by improving contextually the understanding of the impacts of household behavior and efficiency gains in the acceleration of its pathway for economic and environmental benefits.

Economically, the transition to renewable energy creates opportunities for innovation and job creation. This shift, however, is not without challenges. Transition costs, such as infrastructure upgrades and skill retraining, can strain economies, particularly in low-income countries where financial and institutional capacities are limited (Sovacool et al., 2021). Furthermore, regions heavily reliant on fossil fuel industries may face economic dislocation, necessitating robust strategies for economic diversification and just transition (Carley & Konisky, 2020). On the environmental front, the adoption of renewable energy has clear benefits, including reduced greenhouse gas emissions and decreased air pollution. Solar and wind energy systems produce significantly lower lifecycle emissions compared to coal or natural gas (IPCC, 2018). Additionally, the transition alleviates pressure on ecosystems by reducing the extraction of finite resources. However, renewable technologies are not without environmental concerns. The production and disposal of solar panels, wind turbines, and batteries raise issues of resource depletion and waste management (Zappa et al., 2019). Moreover, large-scale renewable projects can disrupt local ecosystems and biodiversity, highlighting the need for careful site selection and stakeholder engagement (González et al., 2022).

The theoretical frameworks underpinning these debates emphasize the role of institutions, technology, and behavioral change. Transition theory, for instance, underscores the importance of niche innovations in challenging incumbent regimes (Geels, 2011). Similarly, ecological economics advocates for integrating environmental limits into economic decision-making, urging a shift from growth-centric paradigms to sustainability-oriented approaches (Daly, 1996). Critics argue that current policies often prioritize technological solutions while neglecting structural inequalities and governance issues (Newell & Mulvaney, 2013).

Energy security and efficiency have been explored in the literature (Alemzero et al., 2021; Lu et al., 2021; Dell'Anna, 2020; Bellos, 2018; Gökgöz & Güvercin, 2018; Lawin et al., 2017; Meierding, 2011). However, they fail to show the dynamic role of the transition level on energy affordability, accessibility, acceptability, and sustainability. In addition, most studies have not considered the four components of energy security (Tufail et al., 2019). Those studies using different methods for this assessment agreed that the collaboration between private and public investment and the improvement of the quality of institutions will benefit the energy sector in terms of shifting to renewable energy (RE) (Lu et al., 2021). Globally, the former studies highlighted the substitution effect of RE for energy imports and benchmarked the performance of countries in RE efficiency (Gökgöz & Güvercin, 2018). The dynamic relationship between explanatory factors and energy security was not explored in the literature, nonetheless, Lu et al. (2021) underlined the relevance of this analysis in national dynamic energy efficiency policies. Although the quality of institutions and public and private actors' collaborations are important to ensure energy, Dato (2017) and Gafa et al. (2022) have shown the benefits of the enhancement in household behavior on the interrelation between the adoption of RE and the investment (monetary and non-monetary) in energy efficiency.

Household capacity to adopt the RE and to invest in energy efficiency can be correlated (Dato, 2017) and influenced by socioeconomic characteristics. This investment lies in reducing energy demand and losses. In addition, these possible synergies can be environmentally friendly in the sense that the adoption can further cut future greenhouse gas (GHG) emissions. Compared to a 10% global average, electricity utilities in Sub-Saharan Africa lose 23% of all energy consumed due to operational inefficiencies, at a cost, according to the AFD (2019), of almost $3.3 billion per year. This research is timely for applying lessons learned from successful experiences and being offered to help utilities identify sources of system losses, develop loss reduction plans, and mobilize finance for investments in efficiency.

West African countries, like those in the rest of the continent, are low-income countries where the potential for renewable energy is high. However, they are currently dependent on fossil fuels for most energy operations, especially in the electricity sector, and solid fuels which are mainly used by the inhabitants. Thus, the sub-region has drafted several renewable energy policies intending to promote the use of renewable energy sources in the energy mix of countries for both electricity generation and other uses (SE4ALL) (ECOWAS, 2013). In Togo, there are the CIZO and ProEnergie I programs, among others. Thus, the ECOWAS region has set a clear objective: to increase the share of renewable energy in the region's overall electricity mix to 10% by 2020 and 19% by 2030. This share would reach 35% in 2020 and 48% in 2030, including large hydroelectric plants. In addition, the region offers a disparity between countries in terms of energy production, export, and import. Policies aim to promote a cleaner environment without affecting economic growth, thereby reducing dependence on non-renewable energy resources for power generation and ensuring energy security and improved social welfare. However, the deployment of renewable is still facing numerous threats, and the consequences are the fuel crisis, energy inefficiency, and households' reluctance to adopt RE and to change their energy consumption behavior. Moreover, the global energy security within ECOWAS countries is lower than 0.5 (Azzuni & Breyer, 2020).

Research questions

The previous sections underline that the African energy transition process is currently threatened by different barriers that can be categorized into governance, financial, projects, political economy factors, enabling skills, and infrastructure, despite the increasing implementation programs. In addition, while not investigated, households' awareness of investing in energy efficiency and adopting clean energy can serve to define incentive policies to advance the energy transition. The shift from duty to clean energy sources is contextually and promptly different. Thus, in the West African context, the main research question of this dissertation is: What are the economic, energy security, and efficiency impacts of renewable energy and energy policies? Especially, the research focuses on the following questions:

- (i): What are the different impacts of renewable energy on energy security and efficiency within ECOWAS countries?
- (ii): What is the investment in energy efficiency impacts of adopting renewable energy in Togo?

- (iii) What are the potential dynamic impacts of energy policies in Togo?

Research objectives

The dissertation assesses the economic and environmental challenges of energy transition within ECOWAS countries. Especially, the research aims to:

i. Assess comparatively the impact of renewable energy (RE) on energy security, and efficiency within ECOWAS countries
ii. Analyze the interaction between households' investment in energy efficiency and adoption of renewable energy in Togo
iii. Simulate the dynamic impacts of energy policies in Togo

Research hypothesis

To reach the above objectives, we formulate the following hypothesis:

- (H1): The higher the share of RE is the higher the country is dynamically securing, and using the energy efficiently
- (H2): Households' adoption of RE positively impacts their investments in EE
- (H3): The energy policies positively impact the economy in Togo.

Value added

This dissertation contributes to the literature by presenting an extensive analysis of the interplay between renewable energy adoption, energy efficiency, and economic development within the ECOWAS region, with a specific focus on Togo. Through a combination of dynamic modeling, empirical analysis, and case studies, this research highlights the critical role of renewable energy (RE) and energy efficiency (EE) in enhancing energy security (ES), fostering economic growth, and mitigating the impacts of climate change. This research aims to make three distinct contributions to the existing energy literature. Firstly, this research uses integrated, national, and regional approaches to provide insights to policymakers on current national energy and environmental policies. In addition, the dissertation contributes to energy transition debates particularly among households by testing the existing energy ladder hypothesis and energy transition management models. Finally, the use of econometric, and simulation models in the research will help to understand the effect of green energy usage and factors affecting household energy choices. This will be relevant to all energy sector players, both at the household and country level. The findings of this research can be used as a policy document by the energy ministry for the promotion of green energy adoption. Also, understanding the energy policies' impacts on fulfilling the national commitment to energy supply in Togo will give impetus to the formulation of subsequent energy and environmental policies.

Thesis defended

Energy policies, such as adopting renewable energy and investing in research and development in the energy sector at both regional and national levels, have the potential to drive sustainable economic growth, to enhance energy security and efficiency.

Dissertation structure

The dissertation is structured into three main essays. The first essay focuses on the comparative assessment of the impact of renewable energy (RE) on energy security and efficiency within ECOWAS countries. The interaction between investment in energy efficiency and the adoption of renewable energy is provided in essay two, while the dynamic impacts of energy policies in Togo based on the computable general equilibrium model are detailed in essay three. The general conclusion and policy brief are discussed in the last section.

Chapter 1: IMPACT OF RENEWABLE ENERGY CONSUMPTION ON ENERGY SECURITY AND EFFICIENCY WITHIN ECOWAS COUNTRIES

Abstract

Although the energy transition appears to be the prerogative of all countries in the fight against energy insecurity and poverty as well as the move towards a world with a stable climate thanks to climate change mitigation it ensures, little is known about its real impact on energy security (ES) and efficiency (EE), particularly in the Economic Community of West African States (ECOWAS). This chapter aims to fill this gap by assessing the impact of renewable energies (RE) on energy security and efficiency in ECOWAS countries. We employ the non-parametric method using the dynamic DEA technique and ARDL estimation on World Bank, Our World in Data, and WGI panel data from 2000 to 2021. The results show that ECOWAS countries are currently experiencing a low EE (0.58), and the growing consumption of renewable energy is positively impacting the ES and EE of the community in the long term. This result is confirmed in Hydropower, Solar Photovoltaic, and Biogas consumption. Comparatively, Cabo Verde presents a high level of EE while Togo's EE is lower (0.36). This suggests that supporting the energy transition in ECOWAS countries is an important pillar for improving EE and ES.

Keywords: Energy security, energy efficiency, renewable energies, pollution, environment

1.1. Introduction

Access to renewable energy is often hailed as a significant game-changer for climate change mitigation and reducing the energy gap. However, its impact on energy security and efficiency remains understudied, particularly in the Economic Community of West African States (ECOWAS) (Akinyemi et al., 2019; Steckel et al., 2019). The existing literature on this topic is riddled with conflicting theoretical debates and empirical findings. The deployment of renewable energy (RE) can significantly influence a country's energy security (ES) and efficiency (EE (Mitrova & Melnikov, 2019; Pérez et al., 2019). The relationship between low-carbon energy production, climate policy, green investment, energy security, and sustained economic growth forms the foundation of the interaction between RE, ES, and EE (Belaïd et al., 2023).

Generally, the geopolitics of renewable energy sources (RES) and energy transition are less contentious than carbon-based energies (Belaïd et al., 2023). However, issues related to pricing and substitution highlight new geopolitical challenges posed by substantial green investments, which could hinder the fight against energy insecurity and inefficiency (Belaïd, 2018; Taghizadeh-Hesary & Yoshino, 2019). Empirical analyses, shaped by timely and contextual factors, reflect these theoretical divergences. The geopolitics of renewable resources suggests that their deployment balances energy supply and demand in the short term and drives green growth in the long term (Ping & Shah, 2023; Wang et al., 2023). Consequently, RE deployment may help address current energy security challenges (Belaïd, 2018; Belaïd et al., 2023). Uniform carbon pricing has raised concerns that RE could elevate energy and economic costs (Belaïd, 2018). Without compensatory measures, climate change mitigation strategies could impede progress toward affordable energy access (Taghizadeh-Hesary & Yoshino, 2019). This theoretical complexity is exacerbated by economic policies that potentially increase greenhouse gas emissions (Wenjie et al., 2022). Investment in energy efficiency (EE) and renewable energy is prominent among human activities that contribute to this complexity.

Concerns about the energy transition are linked to its impacts on EE, energy supply security, sustainability, and competitiveness. Studies by Belaïd (2018) and Hache (2018) have shown that RE can enhance EE and improve ES. This correlation has dominated discussions at various Conference of the Parties (COP) meetings and inspired dynamic empirical research. The increased use of renewable energy promotes decarbonization, supply diversification, and energy competition, which are key components of energy security (Rabbi et al., 2022). Several studies have established the positive impact of RES on EE and ES (Farrow et al., 2018; Li et al., 2020; Su et al., 2021; Zhao & Lin, 2019). However, the political risk channel's influence on the RES-ES-EE relationship is complex and can produce unintended effects (Belaïd, 2018; Belaïd et al., 2023; Belaïd & Massié, 2023). Differences in the former relationships between fossil fuel energy producers, transit routes, and consumers could lead to significant country-specific variations in the direction, significance, and magnitude of these relationships.

While prior studies have explored the diverse impacts of RE on ES and EE, they often focus on geographic regions such as sub-Saharan Africa (Meierding, 2011), North Africa (Ibrahiem & Hanafy, 2021), and the European Union (Gökgöz & Güvercin, 2018; Pérez et al., 2019; Rodríguez-Fernández et al., 2022) without making direct country comparisons. There is a notable lack of comparative studies between African regional countries and various RES. Country-specific factors, including institutional, geopolitical, energy, and economic status, play a crucial role in shaping RE's short- and long-term impacts on EE and ES. Furthermore, previous research has not adequately addressed the dynamic implications of RE investments aligned with sustainability principles. Overall, past studies have primarily focused on the substitution effect of RE for energy imports and benchmarking a country's RE efficiency performance (Gökgöz & Güvercin, 2018).

This research contributes to energy transition, environmental, and climate change policies by assessing the dynamic impact of different RES on ES and EE within ECOWAS countries. Additionally, this research highlights country-specific factors for comparative analysis. The comparative and dynamic analysis is relevant to ECOWAS, as Šprajc et al. (2019) demonstrated the diversity in energy security among the included countries. Their findings showed that ES is advancing in Côte d'Ivoire, Ghana, Nigeria, and Senegal alongside environmental sustainability, achieved through supply and demand-side energy efficiency and developing renewable and other low-carbon energy sources. However, energy equity, defined as the accessibility and affordability of energy supply across the population, is lagging. Niger's focus on environmental sustainability without ensuring energy security underscores the varied energy policies within ECOWAS countries.

ECOWAS countries have begun deploying different RES and enhancing their economies' attractiveness for green technology investments (Lawin et al., 2017). Political concerns related to carbon market mitigation and sustainable development goals have accelerated the growth of RE deployment across the region, potentially impacting ES and EE. For instance, the ECOWAS Renewable Energy Policy aims to create 60,000 mini-grids and 2.6 million stand-alone systems across the region for €13.6 billion to serve 71.4 million people (United Nations, 2015). These goals have led to several projects, programs, and initiatives, including the regional policy to increase energy service access in peri-urban and rural areas, the United Nations Sustainable Energy for All (SE4ALL) initiative, and the revised ECOWAS master plan for power generation and transmission for an integrated regional electricity market. However, institutional, regulatory, legal, and tariff structures remain weak or non-existent in many countries, hindering the energy transition.

Despite the region's efforts to integrate clean energy into total energy consumption, its energy security and efficiency remain huge challenges. Therefore, the question raised in this chapter is: What are the different impacts of renewable energy on energy security and efficiency within

ECOWAS countries? Indeed, this chapter aims to assess the impact of renewable energies (RE) on energy security and efficiency in ECOWAS countries, focusing on the short- and long-term effects of specific renewable energy sources, such as hydropower, solar photovoltaic, wind energy, bioenergy, and renewable energy from municipal waste. The chapter also considers country-specific factors in the RES, ES, and EE relationship. To this end, we employ the non-parametric method using the dynamic DEA technique and ARDL estimation on World Bank, Our World in Data, and WGI panel data from 2000 to 2021. The results show that ECOWAS countries are currently experiencing a low EE (0.58), and the growing consumption of renewable energy is positively impacting the ES and EE of the community in the long term.

The remainder of this chapter is organized as follows: Section 2 describes some statistics on renewable energy sources and different energy security and efficiency programs within ECOWAS countries; Section 3 reviews the literature on the subject; Section 4 details the methodological approach used to achieve the chapter's objectives; Section 5 presents and interprets the empirical results and their econometric analysis; and the conclusion follows in Section 6.

1.2. Current situation on renewable energy sources and different energy security and efficiency programs in ECOWAS countries

The Economic Community of West African States (ECOWAS), comprising 15 member nations, has been progressively prioritizing the adoption of renewable energy sources. Recognizing the critical importance of sustainable energy for regional development, ECOWAS has initiated a range of comprehensive programs aimed at enhancing energy security and efficiency. This section provides a detailed overview of the renewable energy landscape within the ECOWAS region, examining the various initiatives and policies implemented to promote sustainable energy practices. It further delves into the specific programs designed to ensure a reliable energy supply and improve overall energy efficiency, reflecting ECOWAS's commitment to fostering a resilient and sustainable energy future for its member states.

1.2.1. Statistics on renewable energy sources within ECOWAS countries

1.2.1.1. Solar Direct Normal Irradiance (SDNI) resources and existing clean energy Mini-grids

The map in **Figure 1** provides a detailed visualization of existing clean energy mini-grids in West Africa, highlighting their types and distribution across the region. It also shows the Direct Normal

Irradiance (DNI) values, indicating the potential for solar energy harnessing. The types of mini-grids displayed include various combinations of renewable energy sources such as biodiesel/biogas, hybrid photovoltaic (PV) with biodiesel, hybrid hydro with diesel, hybrid PV with diesel, hybrid PV with wind, hybrid PV with wind and diesel, hydro, wind, and PV. This diversity showcases the region's efforts to integrate multiple renewable energy sources to enhance energy access and sustainability.

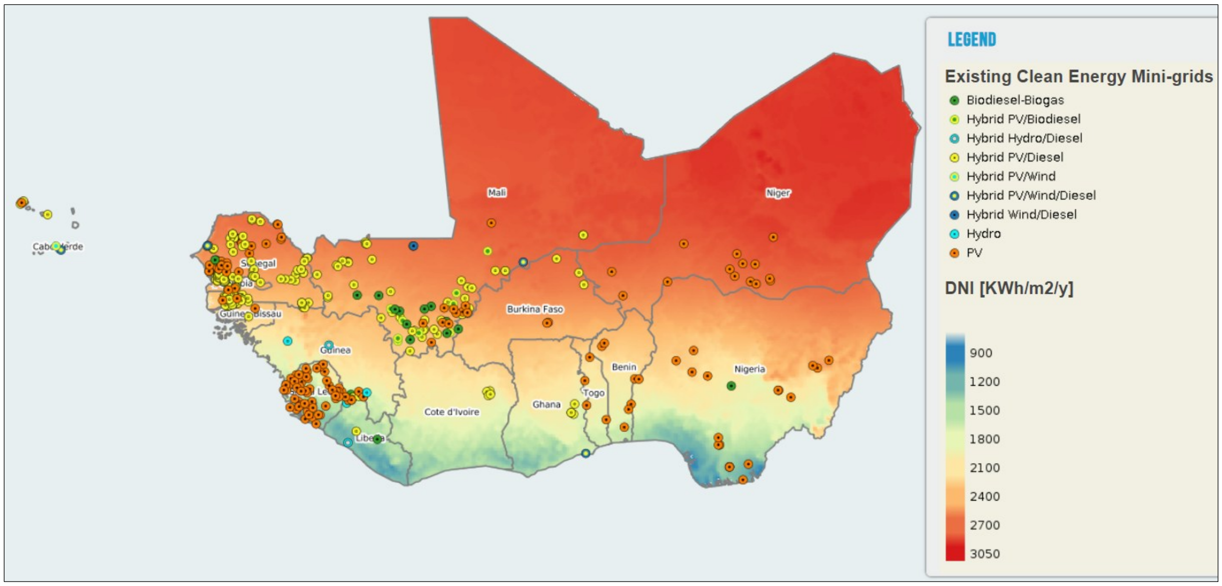

Figure 1: Maps of Solar Direct Normal Irradiance (SDNI) resources and existing clean energy Mini-grids
Source: ECOWREX adapted by the author

In Senegal and Guinea, there is a noticeable concentration of mini-grids, particularly hybrid PV/diesel and hybrid PV/biodiesel systems. This reflects an approach that combines the reliability of diesel with the sustainability of solar energy. Similarly, Sierra Leone and Liberia show a significant number of mini-grids, emphasizing the importance of decentralized energy solutions in these countries. Nigeria exhibits a diverse mix of mini-grids, including hybrid systems and PV standalone setups. The prevalence of these systems indicates a robust move towards leveraging the country's high solar irradiance potential, as reflected by the DNI values. High DNI regions, particularly in northern Nigeria, show substantial potential for solar energy development, which is crucial for reducing dependency on fossil fuels and enhancing energy security. Burkina Faso, Benin, and Togo also feature various clean energy mini-grids, predominantly hybrid PV/diesel and

PV systems. These countries are actively exploring hybrid solutions to address their energy needs, especially in remote and rural areas where traditional grid access is limited.

The background gradient representing DNI values, ranging from 900 to 3050 kWh/m²/year, highlights regions with the highest solar energy potential. Northern parts of Mali and Niger, along with northern Nigeria, show the highest DNI values, indicating excellent conditions for solar energy exploitation. These high irradiance areas are pivotal for future solar energy projects, which can significantly contribute to the region's clean energy transition.

1.2.1.2. Solar Global Horizontal Irradiation (GHI) resources and conventional/thermal on-grid power plants

The map in **Figure 2** presents a comprehensive view of the power plant distribution and types across West Africa, along with the region's solar energy potential as indicated by the Global Horizontal Irradiance (GHI) values. The diversity of power plants, including heavy fuel, coal, natural gas, and diesel, is evident, reflecting the varied energy strategies employed by different countries within the region.

In Senegal, for instance, there is a notable presence of heavy fuel and diesel power plants, both operational and planned, indicating a reliance on these traditional energy sources. Similarly, countries like Guinea, Sierra Leone, and Côte d'Ivoire also show a mix of operational heavy fuel and diesel plants, alongside planned gas plants. This mix highlights a transitional phase where traditional energy sources are still significant while there is a gradual shift towards cleaner alternatives like natural gas. The presence of operational and planned coal plants, marked in black and gray, respectively, is less widespread, yet they play a crucial role in countries like Nigeria and Niger. The map also highlights the presence of natural gas plants, especially in Nigeria and Ghana, showcasing an effort to adopt cleaner energy solutions. The concentration of planned gas plants suggests an ongoing shift towards leveraging natural gas as a more environmentally friendly and efficient energy source.

The GHI gradient, ranging from 1000 to 2800 kWh/m²/year, underscores the region's substantial solar energy potential. High irradiance levels, particularly in countries like Niger, Mali, and northern Nigeria, indicate a significant opportunity to expand solar energy infrastructure. This potential is critical for sustainable development, as it offers a path to reduce reliance on fossil fuels, decrease greenhouse gas emissions, and enhance energy security.

Overall, the map illustrates West Africa's dynamic and evolving energy landscape. The varied types of power plants and their distribution reflect the region's reliance on both traditional and emerging energy sources. The planned developments, especially in natural gas and solar energy, signal a forward-looking approach aimed at diversifying energy sources, improving capacity, and fostering sustainability. This holistic view highlights the region's efforts to balance immediate energy needs with long-term sustainability goals, leveraging its abundant solar resources to create a more resilient and environmentally friendly energy future.

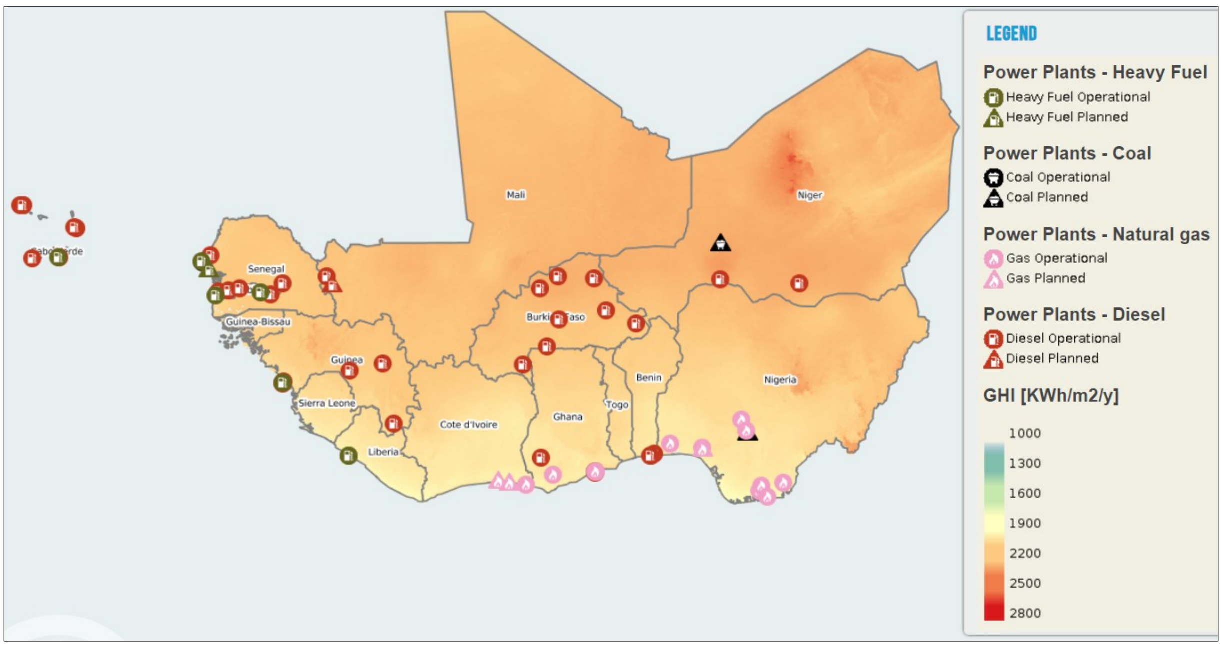

Figure 2: Maps of Solar Global Horizontal Irradiation (SGHI) resources and conventional/thermal on-grid power plants
Source: ECOWREX adapted by author

1.2.1.3. Renewable energy plants within ECOWAS countries

The map in **Figure 3** provides a detailed overview of the renewable energy infrastructure across ECOWAS countries, highlighting the types and statuses of various power plants, including solar (PV and thermal), wind, wave, hydro (small, medium, and large), and biomass. The distribution and development of these plants reflect the region's commitment to diversifying its energy sources and increasing the share of renewables in its energy mix.

Solar power, indicated by orange triangles for operational and planned plants, shows a significant presence across the region. Countries like Senegal, Ghana, and Nigeria have multiple solar projects, both operational and planned, underscoring the region's rich solar potential and the strategic importance of harnessing this abundant resource. Wind power, represented by purple triangles, is less widespread but still notable, especially in coastal areas like Senegal and Ghana. The planned and operational wind plants suggest utilizing coastal and other high-wind areas to complement other renewable sources.

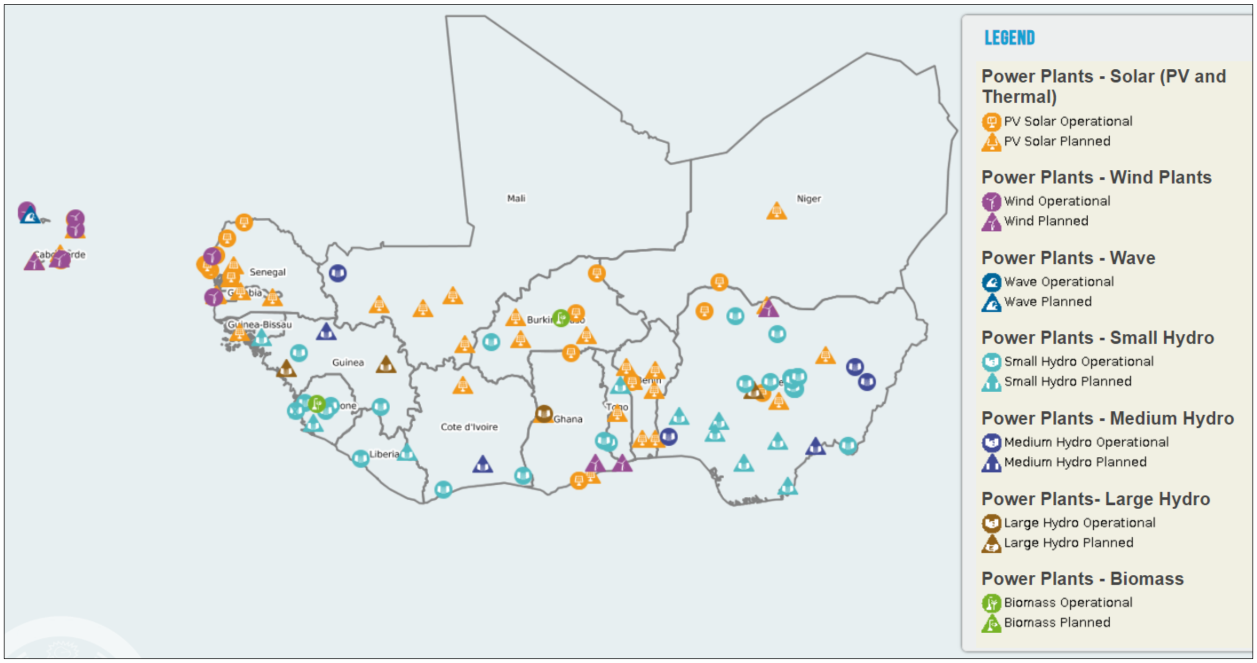

Figure 3: Maps of renewable energy plants
Source: ECOWREX adapted by author

Wave energy, marked with blue triangles, is relatively limited but visible in coastal countries like Senegal and Ghana. The presence of wave power projects highlights an exploration of this relatively untapped resource, which can provide a stable and predictable energy source. Hydropower is well-represented, with small, medium, and large hydro plants marked by shades of blue and brown triangles. Small hydro plants are more widespread, particularly in countries with significant river networks like Côte d'Ivoire and Guinea. Medium and large hydro plants, while fewer in number, are critical for providing substantial power generation capacity, particularly in countries like Ghana and Nigeria. Biomass energy, shown with green triangles, appears to be less common but still significant, particularly in countries with abundant agricultural residues and other organic materials. This form of energy is crucial for utilizing local resources and providing renewable energy in areas where other resources might be limited.

Overall, the map reflects a concerted effort across West Africa to develop a diverse and sustainable energy portfolio. The variety of renewable energy projects, from solar and wind to hydro and biomass, indicates a multifaceted approach to energy security and sustainability. This diversification is essential for mitigating the impacts of climate change, reducing dependency on fossil fuels, and enhancing energy access and reliability across the region. The distribution of these renewable energy projects also suggests a strategic alignment with the region's natural resources and geographical features. Coastal areas leverage wind and wave power, while countries with significant river systems focus on hydroelectric projects. Solar power, with its broad applicability, is widely distributed across the region, taking advantage of West Africa's high solar irradiance levels.

In conclusion, the map illustrates West Africa's proactive approach to developing renewable energy infrastructure, highlighting ongoing and planned projects that aim to create a sustainable and resilient energy future. This strategy not only addresses current energy needs but also positions the region to meet future demand while minimizing environmental impact.

1.2.2. Energy access and use within ECOWAS countries

1.2.2.1. Electricity access within ECOWAS countries

Figure 4 presents data on access to electricity across various countries in West Africa, illustrating the overall population, rural population, and urban population percentages with access. The chart highlights significant disparities between urban and rural areas, as well as between different countries. In most countries depicted, urban populations have a substantially higher access rate to electricity compared to rural populations. For instance, Cabo Verde shows a near-complete access rate for both the general and urban populations at 97.1% and 95.3%, respectively. This suggests a small or negligible rural population or high urbanization rate. Similarly, Nigeria, with 99.7% of its urban population having access to electricity, contrasts sharply with its rural population, where access is only 31.8%.

The disparity is even more pronounced in countries like Burkina Faso and Mali, where rural access is strikingly low at 19.5%, despite relatively higher urban access rates of 71.1% and 89%, respectively. This discrepancy underscores the challenges in extending electricity infrastructure to rural areas in these nations. On the other hand, countries like Ghana and Côte d'Ivoire demonstrate better balance, with Ghana having 91% urban and 37.4% rural access, and Côte d'Ivoire showing 95.3% urban and 70.4% rural access. These figures suggest relatively successful efforts in these countries to extend electricity access beyond urban centres.

Furthermore, countries like Guinea-Bissau and Sierra Leone show significant challenges, with only 37.4% and 29.4% of their populations having access to electricity. These low overall access rates indicate substantial infrastructural and economic barriers. In summary, while urban areas in West Africa generally enjoy higher access to electricity, rural areas lag considerably behind, reflecting broader socio-economic and infrastructural disparities. The data underscores the critical need for targeted policies and investments to bridge this gap and promote equitable development across the region.

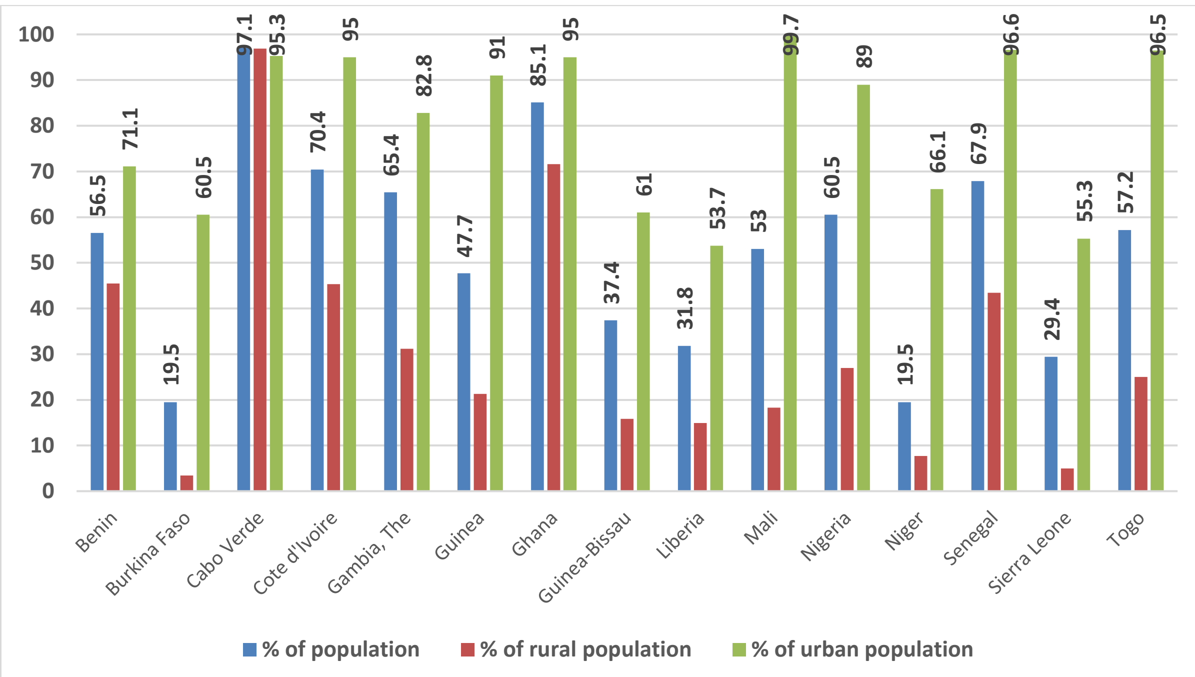

Figure 4: Electricity access in 2022 within ECOWAS countries
Source: Author using World Bank Data

1.2.2.2. Energy use within ECOWAS countries

Figure 5 represents the energy consumption per GDP unit for various ECOWAS countries from 2000 to 2018. These figures reflect the relationship between economic output and energy usage, offering insights into these nations' energy efficiency and economic development trends. A general observation from the data shows diverse trends across the ECOWAS countries, indicating different levels of economic activities, industrialization, and energy efficiency policies. For instance, Benin's energy consumption per GDP increased significantly from 0.539 in 2000 to 1.225 in 2018, indicating a rise in energy intensity. This could be due to increased industrial activities or inefficient energy usage as the economy grows. Burkina Faso also shows a steady increase from

0.293 in 2000 to 0.619 in 2018, though the values remain relatively low, suggesting some improvements in energy efficiency over time.

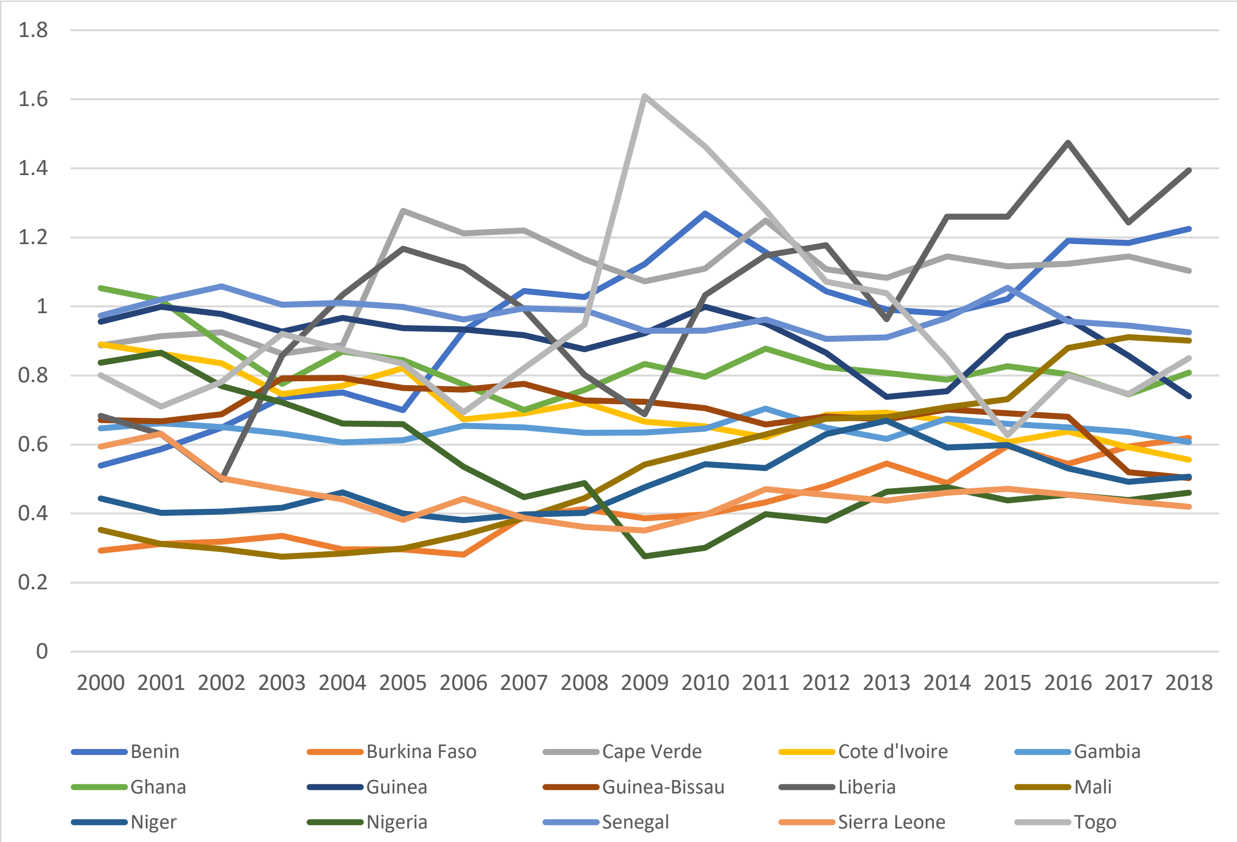

Figure 5: Energy consumption per GDP unit within ECOWAS countries

Source: Author using Our World in Data

Cape Verde presents an interesting case with fluctuations in energy consumption per GDP. It started at 0.887 in 2000, peaked at 1.277 in 2005, and settled at 1.103 in 2018. This fluctuation might be attributed to varying economic activities or shifts in energy policies. Cote d'Ivoire, on the other hand, shows a declining trend from 0.89 in 2000 to 0.556 in 2018, which could indicate improved energy efficiency or structural changes in the economy leading to less energy-intensive activities. Gambia's values remain relatively stable with minor fluctuations, indicating consistent energy consumption patterns relative to GDP. Ghana shows a decline from 1.053 in 2000 to 0.808 in 2018, suggesting improvements in energy efficiency or changes in economic structure. Guinea and Guinea-Bissau exhibit similar stability with minor fluctuations, with Guinea's values decreasing slightly from 0.956 in 2000 to 0.74 in 2018. Liberia demonstrated a significant increase from 0.683 in 2000 to 1.394 in 2018, reflecting rising energy intensity, possibly due to post-conflict reconstruction and economic expansion. Mali, with values starting at 0.353 in 2000 and increasing to 0.901 in 2018, shows gradual growth in energy consumption per GDP, indicating economic development alongside increasing energy use.

Niger maintains relatively low values throughout the period, suggesting a consistent focus on energy efficiency or limited industrialization. Nigeria's values decreased from 0.837 in 2000 to 0.46 in 2018, reflecting improved energy efficiency or a shift towards less energy-intensive economic activities. Senegal's values remain high but stable, indicating a balanced yet high energy consumption pattern relative to GDP. Sierra Leone shows a declining trend from 0.594 in 2000 to 0.42 in 2018, which may indicate improvements in energy efficiency or a structural shift in the economy. Togo exhibits significant fluctuations, peaking at 1.609 in 2008, and then reducing to 0.85 in 2018, reflecting dynamic changes in energy use and economic activities.

Overall, these trends underscore the varying economic and energy landscapes within ECOWAS countries. Countries with increasing energy intensity might need to focus on enhancing energy efficiency and adopting sustainable energy practices. In contrast, countries with decreasing trends should continue to build on their success to ensure sustainable economic growth while managing energy consumption effectively. The data highlights the need for tailored energy policies that align with each country's unique economic and infrastructural context to foster sustainable development across the region.

1.2.2.3. Share of renewable energy in total electricity used

Figure 6 offers an insightful look into the share of renewable energy in the total electricity consumption of various member states within the Economic Community of West African States (ECOWAS) in 2021. These figures reveal significant variations among the countries, reflecting differing levels of commitment, investment, and perhaps geographic and climatic conditions conducive to renewable energy generation. Liberia stands out with the highest share of renewable energy, at 57.61%. This suggests a strong reliance on renewable sources, which could be due to abundant natural resources such as hydroelectric power, which is common in countries with significant river systems. Conversely, Benin has the lowest share at 4.167%, indicating a heavy reliance on non-renewable energy sources such as fossil fuels. This discrepancy highlights the diverse energy landscapes within the ECOWAS region.

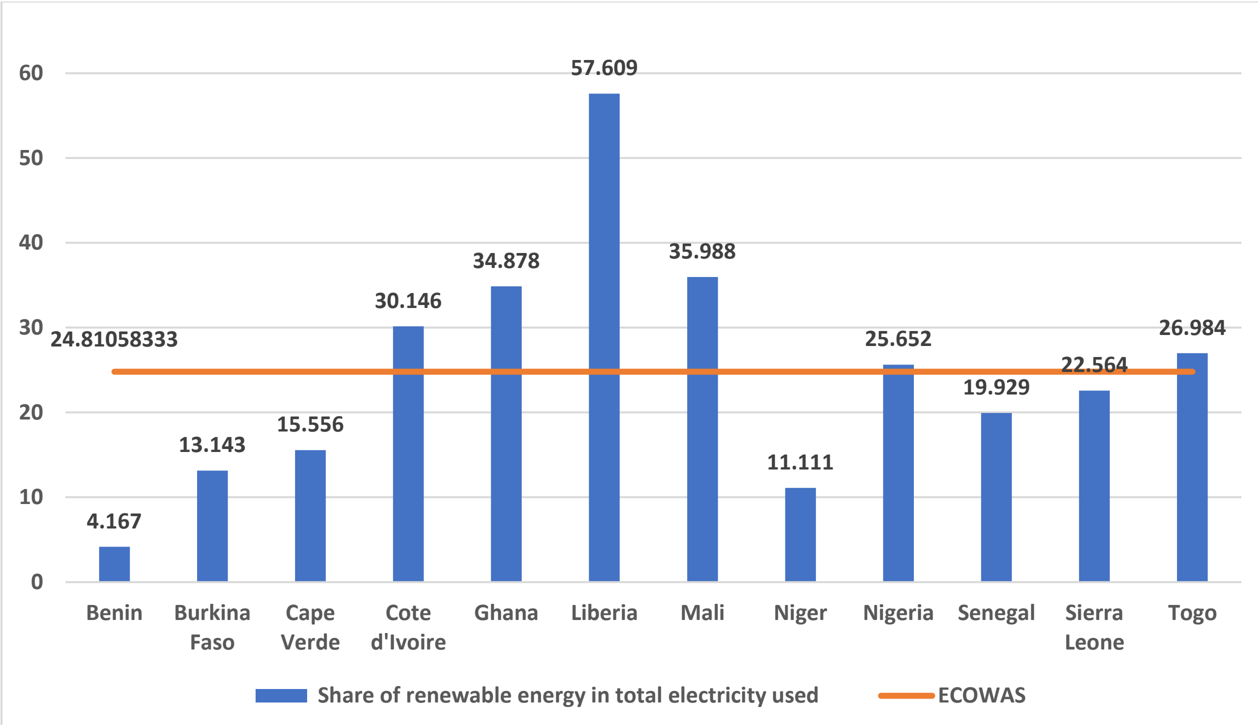

Figure 6: Share of renewable energy in total electricity used in 2021 within ECOWAS countries
Source: Author using Our World in Data

Countries like Ghana (34.88%), Mali (35.99%), and Cote d'Ivoire (30.15%) show relatively high percentages, suggesting substantial investments in renewable energy infrastructure. This might be driven by policy initiatives aimed at increasing energy security and reducing carbon footprints. On the lower end, countries like Niger (11.11%) and Burkina Faso (13.14%) might face challenges such as limited financial resources, less favorable geographic conditions, or insufficient policy frameworks to support the transition to renewable energy. The average share of renewable energy for the entire ECOWAS region stands at approximately 24.81%. This average masks the wide range of values and underscores the need for regional cooperation and knowledge sharing to elevate the renewable energy share in countries that lag. The disparity in renewable energy shares suggests that there is a significant potential for growth and improvement, particularly in countries with lower percentages.

Efforts to boost renewable energy use in the region could include increased investments in infrastructure, technological advancements, and regional collaboration to leverage shared resources and expertise. Additionally, addressing financial and policy barriers can facilitate a smoother transition towards renewable energy, ensuring a more sustainable and resilient energy future for the ECOWAS region.

1.2.3. Renewable energy challenges and programs for energy security in ECOWAS countries.

1.2.3.1. Initiatives for renewable energy development and energy security and efficiency within ECOWAS countries

The Economic Community of West African States (ECOWAS) has been proactive in implementing various programs to enhance renewable energy development, energy security, and efficiency within its member countries. Key initiatives include the ECOWAS Renewable Energy Policy (EREP), which aims to increase the share of renewable energy in the region's energy mix, setting ambitious targets such as achieving 48% renewable electricity generation by 2030. The ECOWAS Energy Efficiency Policy (EEEP) focuses on reducing energy consumption through efficiency measures, with targets like reducing household electricity consumption by 10% by 2020 and 15% by 2030, as well as decreasing losses in electricity distribution. The ECOWAS Centre for Renewable Energy and Energy Efficiency (ECREEE) was established to promote renewable energy and energy efficiency markets. ECREEE supports capacity building, policy development, and investment in sustainable energy projects across the region. The Regional Renewable Energy and Energy Efficiency Policy (RREEEP) guides member states in integrating renewable energy and energy efficiency into their national policies, encouraging harmonization and cooperation. The West African Power Pool (WAPP) aims to integrate national power systems into a unified regional electricity market, ensuring a stable and reliable electricity supply across the region. This includes the development of large-scale renewable energy projects and cross-border electricity trade. In collaboration with the United Nations, ECOWAS has adopted the Sustainable Energy for All (SE4ALL) initiative to provide universal access to modern energy services, improve energy efficiency, and increase the use of renewable energy. The ECOWAS Bioenergy Program focuses on promoting the sustainable production and use of bioenergy, supporting the development of bioenergy policies, sustainable biomass supply chains, and modern bioenergy technologies.

Country-specific initiatives further support these regional efforts. The Solar Nigeria Program aims to provide solar power to off-grid communities, while the National Renewable Energy and Energy Efficiency Policy (NREEEP) in Nigeria focuses on increasing renewable energy adoption and improving energy efficiency across sectors. Ghana’s Renewable Energy Master Plan targets a 10% renewable energy share in the electricity mix by 2030, and the Energy Commission of Ghana implements energy efficiency initiatives such as promoting energy-efficient appliances and conducting public awareness campaigns. In Senegal, the Senergy 2 solar power project contributes significantly to the country’s renewable energy capacity, and initiatives promoting energy efficiency in public buildings aim to reduce energy consumption in public infrastructure. In Côte d'Ivoire, the Scaling Solar Program partners with international organizations to develop large-scale solar projects, and the National Program for Energy Efficiency focuses on reducing energy losses and improving efficiency in industrial and residential sectors. Burkina Faso has set up one of the largest solar plants in West Africa, the Zagtouli Solar Power Station, and its Energy Efficiency Strategy aims to reduce energy consumption through efficiency measures and awareness programs. These programs collectively aim to address the energy challenges in ECOWAS countries by enhancing energy security, increasing access to clean and affordable energy, and promoting sustainable economic development.

1.2.3.2. Challenges for renewable energy development and energy security and efficiency within ECOWAS countries

Despite the ambitious programs and policies, ECOWAS countries face significant challenges in their energy transition efforts. Many ECOWAS countries have inadequate energy infrastructure, including generation, transmission, and distribution facilities. This limits the capacity to integrate and distribute renewable energy effectively. Securing investment in renewable energy projects is a major challenge. Many countries face difficulties in attracting private investment due to perceived risks and lack of financial incentives. Inconsistent and unclear regulatory frameworks can deter investment and hinder the development of renewable energy projects. Additionally, there is often a lack of enforcement of existing policies. There is a shortage of skilled professionals and technical expertise needed to develop, operate, and maintain renewable energy systems. This gap affects the implementation and sustainability of energy projects. Limited access to modern and efficient renewable energy technologies impedes progress. High costs and the lack of local manufacturing capabilities further exacerbate this issue. High poverty levels and low purchasing power restrict the ability of households and businesses to invest in renewable energy solutions. Additionally, there can be resistance to change due to a lack of awareness or cultural factors. Political instability and weak institutional structures can disrupt the implementation of energy policies and projects. Corruption and bureaucratic inefficiencies also pose significant obstacles.

The variability of renewable energy sources like solar and wind, coupled with the impacts of climate change, can affect the reliability and stability of renewable energy supplies. Addressing these challenges requires coordinated efforts at national and regional levels, involving governments, private sector stakeholders, and international partners. Strengthening regulatory frameworks, enhancing financial mechanisms, building technical capacity, and fostering regional cooperation are essential steps towards achieving a sustainable energy transition in the ECOWAS region.

1.3. Theoretical foundation and empirical evidence of the impact of renewable energy consumption on energy security and efficiency

Integrating renewable energies (RE) into the energy and electricity mix is a critical component of energy transition policies and the fight against climate change. This shift aims to replace non-renewable energy sources with sustainable alternatives, fostering environmental sustainability and enhancing energy security (Hache, 2018). Theoretical frameworks supporting this transition draw from paradigms such as energy transition, climate policy, green investment, and sustained economic growth (Belaïd et al., 2023; Hache, 2018). The adoption of renewable energies is posited to mitigate geopolitical conflicts and promote global stability by reducing dependence on carbon-based fuels (Mitrova & Melnikov, 2019; Pérez et al., 2019; Szulecki & Kusznir, 2018).

The relationship between renewable energy adoption and economic growth is central to the theoretical framework for energy transition. Renewable energy development creates jobs, stimulates innovation, and enhances energy security, all of which contribute to sustained economic growth. For instance, the renewable energy sector has become a significant source of employment, with millions of jobs created worldwide in solar, wind, and biomass industries (Pérez et al., 2019). Moreover, renewable energy systems reduce the economic risks associated with fossil fuel dependence, such as price volatility and supply disruptions. By diversifying the energy mix, countries can stabilize energy prices and improve their trade balances, freeing resources for other developmental priorities (Mitrova & Melnikov, 2019).

The economic benefits of renewable energy adoption extend to the household level, where access to affordable and reliable energy enhances productivity and quality of life. This dynamic is particularly significant in developing countries, where renewable energy systems can provide electricity to underserved communities, unlocking new opportunities for economic participation (Belaïd et al., 2023).

Renewable energy adoption also has profound geopolitical implications, shaping the balance of power in the global energy landscape. By reducing dependence on fossil fuels, renewable energy mitigates the geopolitical conflicts associated with resource scarcity and energy transit routes. For example, the shift to domestic renewable energy production reduces reliance on energy imports, enhancing national energy security and autonomy (Hache, 2018).

In addition, the renewable energy transition fosters international stability by promoting cooperation and reducing competition for finite resources. Collaborative renewable energy projects, such as cross-border power grids and regional energy markets, exemplify the potential for renewables to strengthen diplomatic ties and support global stability (Pérez et al., 2019).

Energy security (ES) is traditionally defined as the availability of reliable and affordable energy supplies. The orthodox view suggests that renewable energy investments enhance ES by improving energy availability, accessibility, acceptability, and affordability in both the short and long term (Azzuni et al., 2020; Rodríguez-Fernández et al., 2022; Sadik-Zada & Gatto, 2021). Renewable energy provides a buffer against supply-demand fluctuations, supporting economic stability (Ping & Shah, 2023), and addresses environmental concerns, promoting sustainable development (Wang et al., 2023). The inexhaustible nature of renewable resources, combined with their minimal environmental impact, underscores their potential to enhance ES without the geopolitical risks associated with fossil fuels.

The relationship between ES and renewable energy is multifaceted, balancing economic, environmental, and social factors. Renewable sources such as solar, wind, and hydroelectric power offer a sustainable alternative to fossil fuels, reducing greenhouse gas emissions and mitigating climate change. This transition supports global efforts to achieve net-zero emissions and fosters a cleaner, healthier environment. Additionally, renewable energy systems can be deployed in various scales and locations, enhancing energy resilience and reducing dependency on centralized power grids.

One primary advantage of renewable energy in enhancing ES is its ability to diversify energy sources. A diversified energy mix reduces the vulnerability of energy systems to disruptions caused by geopolitical tensions, natural disasters, or supply chain issues. Countries heavily reliant on imported fossil fuels are susceptible to price volatility and supply disruptions due to political instability in supplier regions. By investing in renewable energy, these countries can reduce their reliance on imported fuels, thereby enhancing their energy independence and security.

Energy efficiency (EE) refers to the optimal use of energy to achieve economic output while minimizing waste. The transition to renewable energy promotes technologies that enhance resource productivity rather than merely increasing resource throughput (Belaïd et al., 2023). This aligns with the principles of sustainable development, which prioritize long-term environmental and economic health. However, the impact of climate mitigation measures on economic growth and equality remains contentious. Uniform carbon pricing can increase energy costs and economic burdens, potentially hindering progress toward affordable energy access (Belaïd, 2018; Taghizadeh-Hesary & Yoshino, 2019).

Renewable energy also contributes to energy accessibility, particularly in remote or underserved areas. Decentralized renewable energy systems, such as microgrids and off-grid solar installations, can provide electricity to communities not connected to the main power grid. This improves quality of life, supports economic development, and reduces energy poverty. In many developing countries, renewable energy projects have successfully brought electricity to rural areas, enabling access to education, healthcare, and economic opportunities.

The environmental benefits of renewable energy are well-documented. Renewable energy sources produce little to no greenhouse gas emissions during operation, significantly reducing the carbon footprint of energy production. This is crucial for mitigating climate change and its associated impacts, such as extreme weather events, sea level rise, and biodiversity loss. Additionally, renewable energy systems generally have lower environmental impacts compared to fossil fuel extraction and combustion, which can cause air and water pollution, habitat destruction, and health problems for local communities.

Economic stability is another key aspect of ES that can be bolstered by renewable energy investments. In the short term, renewable energy projects create jobs and stimulate economic growth. The renewable energy sector is labor-intensive, requiring diverse skills for manufacturing, installation, operation, and maintenance of renewable energy systems. This job creation can help offset job losses in the fossil fuel industry and support a just transition to a low-carbon economy. Furthermore, renewable energy projects can attract investment and drive innovation, fostering economic development and competitiveness.

In the long term, renewable energy can contribute to sustainable economic development by providing a stable and affordable energy supply. Unlike fossil fuels, which are subject to price fluctuations and depletion, renewable energy sources are abundant and inexhaustible. This stability can reduce the economic risks associated with energy price volatility and support long-term planning and investment. Additionally, renewable energy can enhance energy affordability by reducing the cost of electricity generation. As technology matures and economies of scale are achieved, the cost of renewable energy continues to decline, making it increasingly competitive with traditional energy sources.

However, the transition to renewable energy is not without challenges. One major obstacle is the intermittent nature of some renewable energy sources, such as solar and wind power. These sources are dependent on weather conditions and time of day, which can lead to variability in energy supply. Advancements in energy storage technologies, such as batteries, are essential to address this issue. Energy storage systems can store excess energy generated during periods of high production and release it during periods of low production, ensuring a reliable and stable energy supply.

Another challenge is the need for substantial investments in infrastructure to support the integration of renewable energy into existing energy systems. This includes upgrading power grids, developing energy storage solutions, and creating supportive policies and regulatory frameworks. Governments and private sector stakeholders must collaborate to mobilize the necessary financial resources and create an enabling environment for renewable energy development.

The social implications of renewable energy transitions also warrant consideration. While renewable energy projects can bring numerous benefits, they can also pose challenges for local communities. For instance, large-scale renewable energy installations, such as wind farms and solar parks, can lead to land use conflicts, displacement of local populations, and changes in land ownership patterns. It is essential to ensure that renewable energy projects are developed in a socially inclusive and equitable manner, with the active participation and consent of affected communities.

Moreover, the impact of climate mitigation measures on economic growth and equality remains contentious. While renewable energy investments can drive economic growth, policies aimed at reducing carbon emissions, such as carbon pricing, can have complex economic implications. Uniform carbon pricing, for instance, can increase energy costs for consumers and businesses, potentially exacerbating economic inequalities. Policymakers must carefully design and implement climate policies to balance environmental goals with economic and social considerations.

Renewable energy has the potential to significantly enhance energy security by improving energy availability, accessibility, acceptability, and affordability. In the short term, renewable energy can provide a buffer against supply-demand fluctuations, supporting economic stability. Over the long term, it addresses environmental concerns and promotes sustainable development. The transition to renewable energy is closely linked to improvements in energy efficiency, which enhances resource productivity and aligns with the principles of sustainable development. However, the transition is not without challenges, including the intermittent nature of some renewable energy sources, the need for substantial infrastructure investments, and the social implications of renewable energy projects. Policymakers and stakeholders must work together to address these challenges and ensure a just and equitable transition to a sustainable energy future. By doing so, they can unlock the full potential of renewable energy to enhance energy security, mitigate climate change, and promote sustainable development for all.

The transition to renewable energy sources (RES) presents a multifaceted impact on energy security (ES) and energy efficiency (EE), with evidence showing a complex interplay of benefits and challenges. Investments in renewable energy infrastructure can bolster a region's capacity to meet energy demands and stimulate economic growth in the short term. Long-term effects are equally significant, contributing to sustainable development by mitigating environmental impacts and reducing greenhouse gas emissions, thereby promoting green growth (Wang et al., 2023). However, this transition is fraught with obstacles that require careful consideration.

One primary challenge in shifting to renewable energy is the potential economic impact of climate mitigation policies. These policies, while essential for reducing carbon emissions, can sometimes lead to economic slowdowns and increased energy costs if not balanced with measures that ensure economic stability and equity (Belaïd et al., 2023). The economic implications are particularly pronounced in regions heavily dependent on fossil fuels, where the transition can disrupt existing industries and labor markets. This disruption necessitates policies that support economic diversification and provide a safety net for affected workers.

Geopolitically, the renewable energy transition introduces new dynamics. While renewable energy can reduce conflicts over traditional fossil fuel resources, it creates dependencies on materials critical for renewable technologies, such as rare earth minerals. Concentrating these minerals in specific regions can lead to new geopolitical tensions and dependencies, as countries vie for control over these essential resources (Taghizadeh-Hesary & Yoshino, 2019; Belaïd, 2018). Additionally, the decentralization of energy production inherent in renewable systems can reshape traditional energy relationships, potentially leading to conflicts between established energy producers and emerging renewable energy sectors (Hache, 2018).

Comparative studies have examined the impact of RES on ES and EE in various regions, but there is a lack of comparative analysis between African regional countries (Meierding, 2011; Ibrahiem & Hanafy, 2021; Gökgöz & Güvercin, 2018; Pérez et al., 2019; Rodríguez-Fernández et al., 2022). This research addresses this gap by analyzing the dynamic impact of RES on ES and EE within ECOWAS countries, considering their specific contexts, and applying appropriate methodologies. The research uses a Dynamic Development Envelop Analysis (DDEA) model with undesirable outputs to assess EE and Principal Component Analysis (PCA) to measure ES. This approach contributes to the literature by providing a dynamic analysis of ES and EE in ECOWAS countries, highlighting the importance of renewable energy in enhancing energy security and efficiency.

1.4. Methodological approach to the impact of renewable energy consumption on energy security and efficiency

1.4.1. Energy security conceptualization

The concept of security is typically defined as the absence of any threat factors (Aslantürk & Kıprızlı, 2020). However, energy security (ES) is multifaceted and influenced by numerous factors. Sharifuddin (2014) identified five core aspects of energy security: availability, stability, affordability, consumption efficiency, and environmental impact. Prior definitions were limited to energy and economic aspects, excluding the social dimension (Sun et al., 2020). Yao & Chang (2014) offered a comprehensive definition, describing an energy-secure nation as one with affordable energy resources, an adequate supply of fossil fuels, nuclear energy, renewable resources, applicable technologies, and attention to social and environmental concerns. Given the lack of consensus on the definition of energy security, its assessment varies contextually, temporally, and based on the challenges addressed by the study. Escribano et al. (2013) and Lucas et al. (2016) examined the multidimensional aspects, categorizing energy risks into primary, secondary, and exposure risks (**Figure 7**). Primary risks include socioeconomic or technical

causes, secondary risks involve energy supply interruptions or damages to the environment, property, and human health, and exposure risks encompass market volatility and vulnerability.
The current definition of energy security now includes various dimensions such as energy dependency, energy supply adequacy, diverse generation types, access to energy, reasonable pricing, international relations, and environmental sustainability (Sarangi et al., 2019). Different countries exhibit variations in their quality of life and development levels, as indicated by their energy use per capita (Gasser, 2020). Therefore, rather than assessing energy security as a unidimensional element, we employ Principal Component Analysis (PCA) on environmental, supply, and competitiveness dimensions (Alemzero et al., 2021; Valdés, 2018; Lucas et al., 2016). Principal Components Analysis (PCA) is a statistical technique used to reduce the dimensionality of a dataset while preserving as much variability as possible. It transforms the original variables into a new set of uncorrelated variables called principal components, which are ordered by the amount of variance they capture from the data. The first principal component explains the maximum possible variance, followed by the second, and so on. PCA is grounded in linear algebra and eigenvalue decomposition, relying on the covariance or correlation matrix of the data. One of the main advantages of PCA is its ability to simplify complex datasets, making them easier to visualize and interpret without significant loss of information. It is particularly useful in identifying patterns, eliminating multicollinearity, and enhancing the performance of predictive models by reducing noise and redundancy. PCA is also valuable in exploratory data analysis, especially when dealing with large datasets containing many interrelated variables. By concentrating information into a few components, PCA supports efficient data processing and facilitates better understanding of underlying structures. However, it is important to note that PCA is a linear method and may not capture nonlinear relationships. Despite this, its computational efficiency and interpretability make it a widely used tool in various scientific fields.

The indicators integrated into each dimension are detailed in **Figure 7**. This method was applied by Šprajc et al. (2019) in their methodological analysis of the energy trilemma index in 125 countries. Their results, including ECOWAS countries (Benin, Côte d'Ivoire, Ghana, Niger, Nigeria, Senegal), show that energy security is advancing in Côte d'Ivoire, Ghana, Nigeria, and Senegal with environmental sustainability assessed through supply and demand-side energy efficiency and the development of renewable and low-carbon energy sources. However, Niger has prioritized environmental sustainability without ensuring energy security, confirming that energy policies within ECOWAS countries differ according to specific national characteristics.

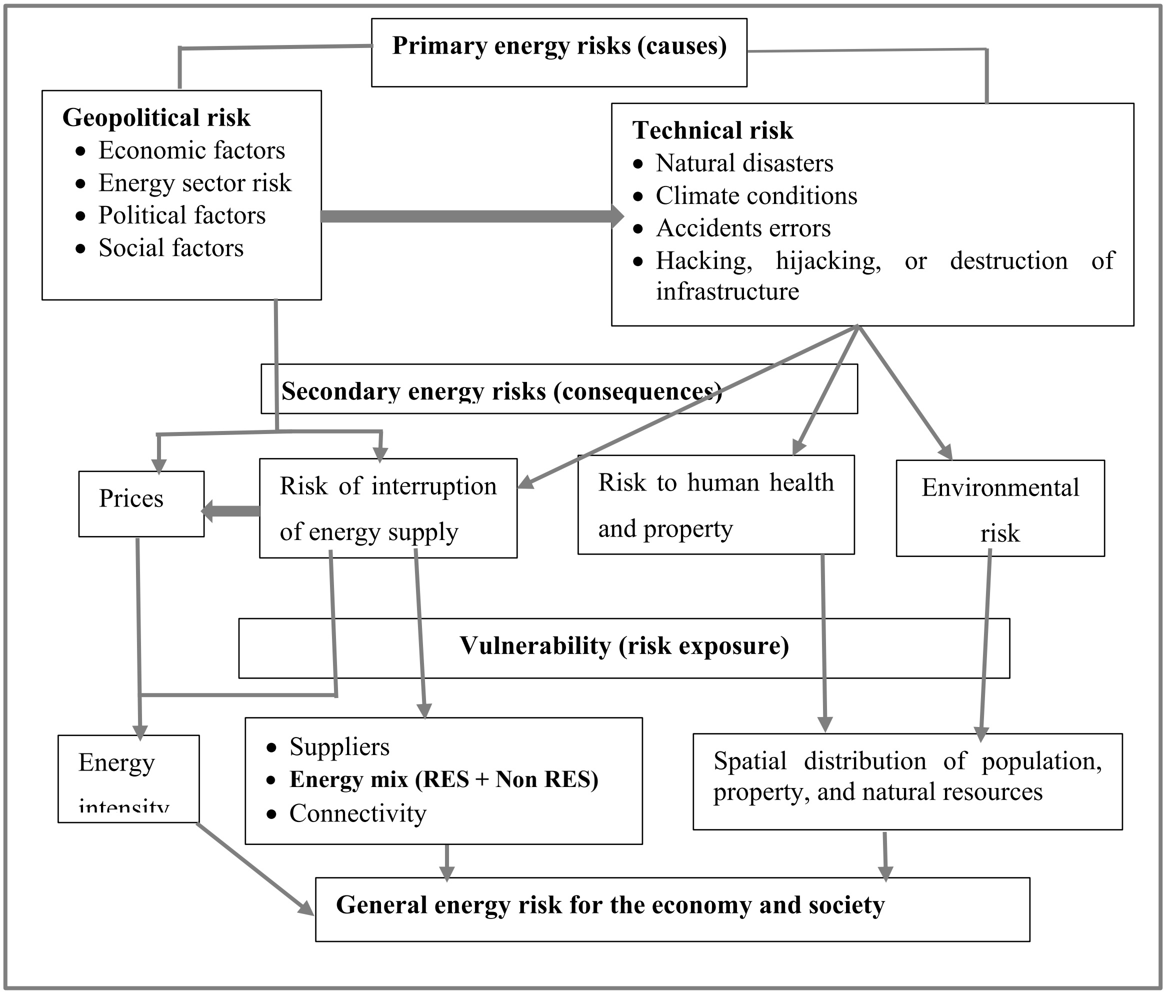

Figure 7: Energy risk factors
Source: Authors following Escribano et al. (2013)

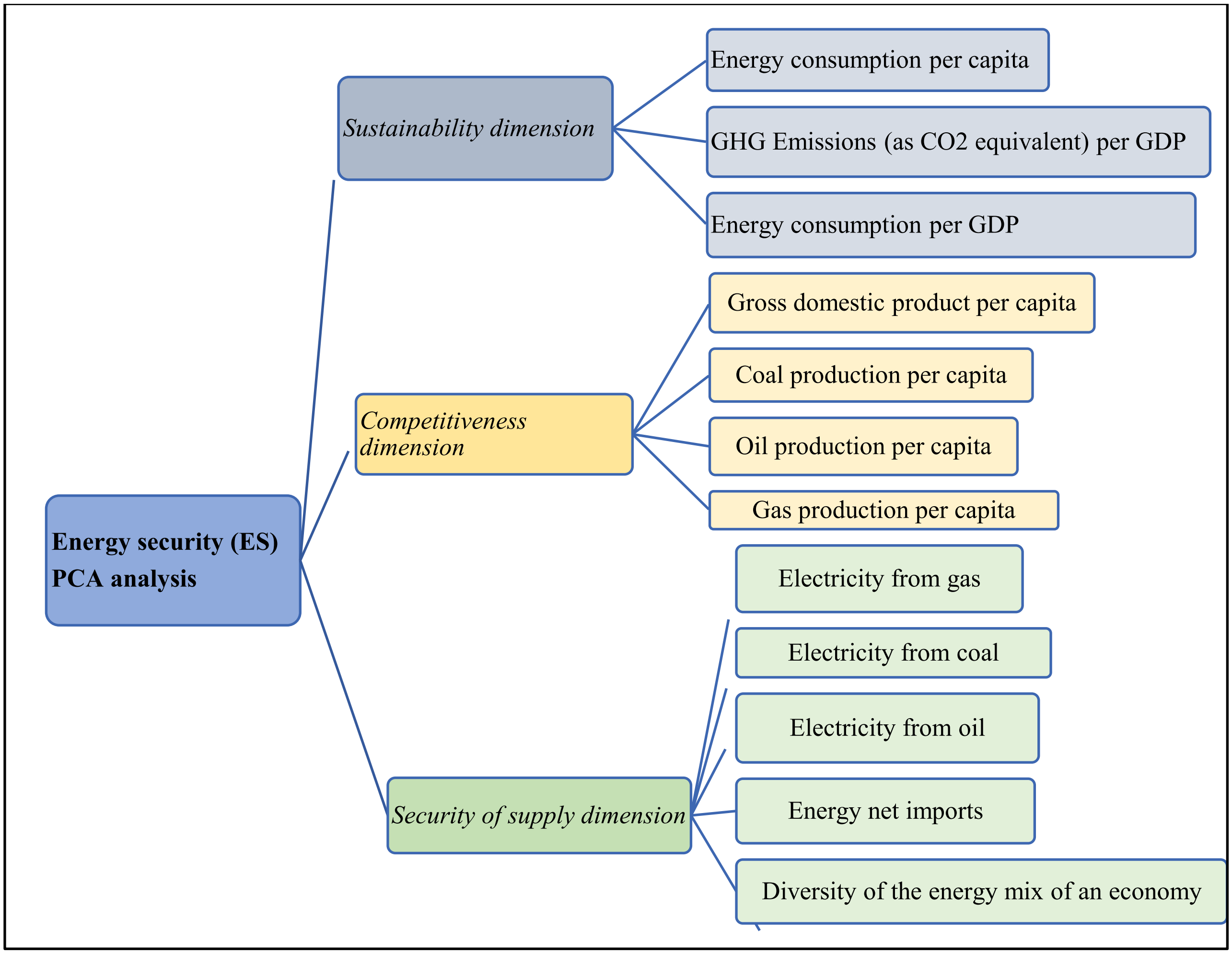

Figure 8: Energy security dimensions and indicators

1.4.2. Dynamic Energy efficiency assessment

Parametric and non-parametric approaches are commonly used in efficiency studies. The parametric or econometric methods require the production function specification and allow to capture of the exogenous factors' effects on efficiency (Honma & Hu, 2018). The quadratic production function is used as well as the translog function to estimate the production function. However, because quadratic functional form input SFA failed to converge on the data, we follow translog functional form as a conventional method. In addition, the parametric approaches in general, are influenced by the econometric specification and do not allow to separate outputs from desirable to undesirable (Lu et al., 2021). In contrast, the non-parametric approaches consider the inadequacy of input and output slacks and carry-over slacks, which address the time accumulation effect in the analysis. That is, using the Dynamic Slack-Based Measures model, this research proposes a national dynamic energy efficiency after accounting for the undesirable output of carbon dioxide emission. The Slack-based Measures (SBM) model is a general form of distance function measure wherein the inputs and outputs are free to have different distance parameters. This method does not require the pre-determination of parameters; the weights are defined using a mathematical approach, which makes the analysis objective (Lu et al., 2016).

Following Lu et al. (2021), the national dynamic energy efficiency assessment was divided into input and output. Capital, labor force, and energy consumption were used as inputs, while GDP and carbon dioxide emissions were used as desirable and undesirable outputs, respectively. Capital, which exhibits an annual carry-over characteristic, at the end of the period t was carried forward to the period $t+1$ to measure the dynamic energy efficiency of the period $t+1$. Carry-over was used to assess the annual operational performances of countries to obtain their long-term dynamic energy efficiency. The efficiency values were calculated after considering energy consumption and environmental impact factors. Lu et al., (2021) present the assessment framework and show that capital is the carry-over carried from one term to another (Owjimehr et al., 2023). Non-oriented efficiency (TE_o) admits the optimal from the following program when the target decision-making unit (DMU) is affirmed to be overall efficient:

$$TE_o = min \frac{\frac{1}{T}\sum_{t=1}^{T}\left[1-\frac{1}{m+q+nfree}\left(\sum_{i=1}^{m}\frac{s_{it}^{-}}{x_{iot}}+\sum_{p=1}^{q}\frac{s_{pt}^{b-}}{y_{pot}^{b}}+\sum_{h=1}^{nfree}\frac{s_{ht}^{free-}}{z_{hot}}\right)\right]}{\frac{1}{T}\sum_{t}^{T}\left[1+\frac{1}{s+nfree}\left(\sum_{r=1}^{s}\frac{s_{rt}^{+}}{y_{rot}}+\sum_{h=1}^{nfree}\frac{s_{ht}^{free+}}{z_{hot}}\right)\right]} \tag{1.1}$$

$\boldsymbol{S.T.}$

$$x_{iot} = \sum_{j=1}^{n} x_{ijt}\lambda_j^t + s_{it}^{-}, (i = 1, \dots, m; t = 1, \dots, T) \tag{1.2}$$

$$y_{rot} = \sum_{j=1}^{n} y_{rjt}\lambda_j^t - s_{rt}^{+}, (r = 1, \dots, s; t = 1, \dots, T) \tag{1.3}$$

$$y_{pot}^{b} = \sum_{j=1}^{n} y_{pjt}^{b}\lambda_j^t + S_{pt}^{b-}, (p = 1, \dots, q; t = 1, \dots, T) \tag{1.4}$$

$$\sum_{j=1}^{n} z_{hjt}\lambda_j^t = \sum_{j=1}^{n} z_{hjt}\lambda_j^{t+1}, (\forall h; t = 1, \dots, T-1) \tag{1.5}$$

$$z_{hot} = \sum_{j=1}^{n} z_{hjt}\lambda_j^t - S_{ht}^{free+}, (h = 1, \dots, nfree; t = 1, \dots, T) \tag{1.6}$$

$$z_{hot} = \sum_{j=1}^{n} z_{hjt}\lambda_j^{t+1} + S_{ht}^{free-}, (h = 1, \dots, nfree; t = 1, \dots, T-1) \tag{1.7}$$

$$\sum_{j=1}^{n} \lambda_j^t = 1, (t = 1, \dots, T) \tag{1.8}$$

$$\lambda_j^t \geq 0, s_{it}^{-} \geq 0, s_{rt}^{+} \geq 0, s_{pt}^{b-} \geq 0, s_{ht}^{free+} \geq 0, s_{ht}^{free-} \geq 0 \tag{1.9}$$

Where s_{it}^{-}, s_{rt}^{r}, s_{pt}^{b-}, s_{ht}^{free+}, and $s_{ht}^{free-}$are the input excess, desirable output shortfall, undesirable output excess, carry-over output shortfall at a time t, and carry-over input excess at a time $t+1$; x_{iot}, y_{rot}, and y_{pot}^{b} delineate the constraints for the inputs and desirable and undesirable outputs, and Equations (1.5), (1.6), and (1.7) specify the carry-over items as being freely determined while satisfying the continuity assumption between inputs and outputs. At time t, the intensity of DMU_j is given by λ_j^t and the optimal solution to this program is a value ranging between 0 and 1 for each DMU when all the excesses and shortfalls are 0. Thereby, the target DMU is affirmed to be overall efficient when $TE_o^* = 1$ in Equation (1.1). The inputs and output variables for the EE assessment are presented in **Table 1.**

$$TE_{ot}^* = \frac{\left[1 - \frac{1}{m+q+nfree}\left(\sum_{i=1}^{m} \frac{s_{it}^{-*}}{x_{iot}} + \sum_{p=1}^{q} \frac{s_{pt}^{b-*}}{y_{pot}^{b}} + \sum_{h=1}^{nfree} \frac{s_{ht}^{free-*}}{z_{hot}}\right)\right]}{\left[1 + \frac{1}{s+nfree}\left(\sum_{r=1}^{s} \frac{s_{rt}^{+*}}{y_{rot}} + \sum_{h=1}^{nfree} \frac{s_{ht}^{free+*}}{z_{hot}}\right)\right]} \tag{1.10}$$

1.4.3. RES impact on energy security (ES), and efficiency (EE)

Efficient and secure energy management draws its theoretical and methodological foundations from the new growth theory. Following the conceptual framework and the relationship described in the literature between techno-economic variables and the energy mix, it is necessary to introduce renewable energy (RE) consumption into the analysis of energy efficiency and security (Owjimehr et al., 2023). In previous studies, various variables have been proposed regarding the purpose as determinants of ES and EE. However, based on the purpose of the research, we consider RE as the primary explanatory variable and expect a positive impact. Owjimehr et al. (2023); and Lu et al. (2021) used the proportion of coal and oil consumption in total energy consumption and found that an increase in this ratio leads to an increase in industrial production and, as a result, improves production and energy management. However, they believed that reducing this ratio would increase production efficiency, and by increasing the ratio of renewable energies, the energy structure would improve, and along with the improvement of production technology, energy management would also increase. Furthermore, we decompose the total RE impact on specific effects related to different RE sources such as Renewable hydropower (HP), Onshore wind energy (Wind), Solar photovoltaic (SP), Bioenergy, Renewable energy from municipal waste (Waste), and Biogas. In addition to RE, we add Gross domestic product per capita (GDP_{hbt}), demographic growth (DG) consumer price (P), human capital (HCA) approximated by secondary school enrolment, and institutional quality (INQ) index obtained by applying principal component analysis (PCA) on six institutional variables (corruption control, government effectiveness, political stability and absence of violence and terrorism, regulatory quality, rule of law, and voice and accountability).

Adding these variables is governed by certain literature assumptions. Consumer price and Institutional quality are ambiguously affecting energy security or efficiency. Price increases can lead to a shift towards the use of lower-quality materials and negatively affect ES and EE (Yang & Wei, 2019). However, Lu et al. (2021) showed that companies' technological innovation can inverse the price effect by reducing the share of energy in production. Intuitively, low institutional quality dampens capital productivity by various means, paralyzes government action in favor of public welfare, and encourages rent-seeking behavior. However, given the existence of heavy economic policies, economists argue that a certain degree of low institutional quality is the catalyst for economic development (Kalyuzhnova & Belitski, 2019). Therefore, the model followed in the present research is an arithmetic transformation of the Cobb-Douglas energy demand function $[f(RE_{it}, GDP_{hbt_{it}}, P_{it}, DG_{it}, HCA_{it}, INQ_{it};\ \theta)]$ (Adom et al., 2021; Owjimehr et al., 2023).

$$f(RE_{it}, GDP_{hbt_{it}}, P_{it}, DG_{it}, HCA_{it}, INQ_{it};\ \theta) = ARE_{it}^{\theta_{RE}} GDP\_hbt_{it}^{\theta_{GDP\_hbt}} P_{it}^{\theta_p} DG_{it}^{\theta_{DG}} HCA_{it}^{\theta_{HCA}} INQ_{it}^{\theta_{INQ}} \quad (1.11)$$

Following Owjimehr et al., (2023); and Adom et al., (2021), the transformation of **Equation (1.11)** gives energy efficiency or security (e_{it}) equation specified as (1.12) with X the vector of control variables:

$$e_{it} = \alpha + \theta_{RE} RE_{it} + \theta_{kt} X_{it} + u_i + \vartheta_t + \varepsilon_{it} \quad (1.12)$$

1.4.4. Data source and descriptive statistics

The focus of this research is on energy efficiency and security, which are the dependent variables in our model. Following Lu et al. (2021); using the dynamic Slacks-base measures methodology with dynamic development envelopment analysis (DDEA), we assess energy efficiency. Concerning energy security measurement, we use principal component analysis (PCA) following energy trilemma index assumptions (Šprajc et al., 2019). The two indexes are captured for the fifteen ECOWAS countries from 2000 to 2021. The sample includes Benin, Burkina Faso, Cabo Verde, Cote d'Ivoire, The Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone, and Togo.

For calculating energy efficiency, we consider data labor, capital, and energy consumption as input variables (Owjimehr et al., 2023) and GDP as desirable output and dioxide carbon emissions as undesirable output (Lu et al., 2021) from World Bank Indicators (WDI). This indicator for all ECOWAS countries is calculated and plotted in **Figure 9**. This figure shows heterogeneity in the EE range between Cabo Verde the best energy performer (0.90) and Togo the lower performer (0.36). On average, ECOWAS countries are low energy efficient (0.58), and more than two-thirds of countries (10) have their EE below this average.

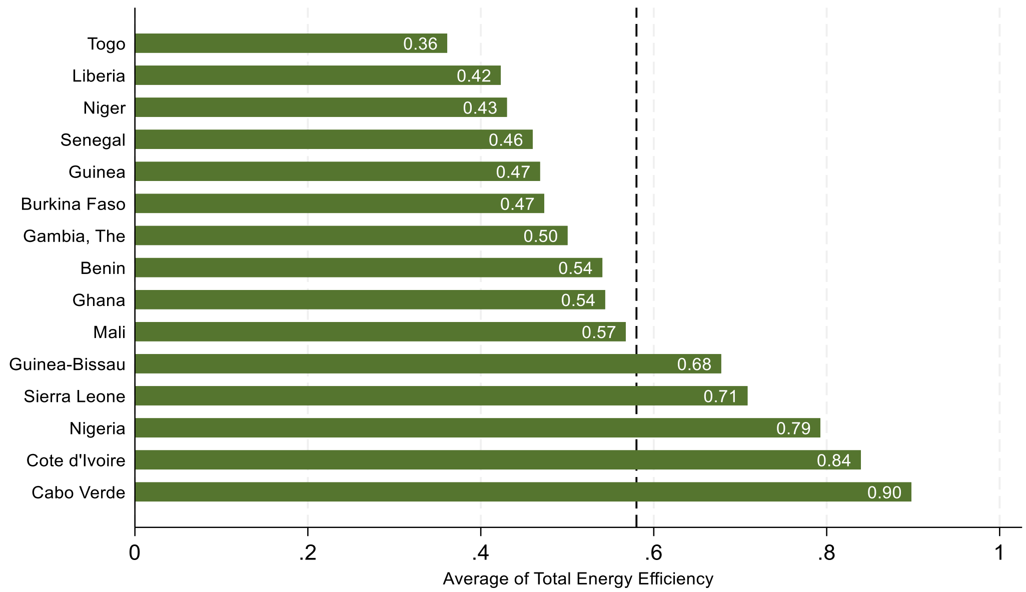

Figure 9: Energy efficiency within ECOWAS countries

Factors included in energy security (ES) calculation are mostly data from Our World in Data (Owid). Sustainability, competitiveness, and supply security components are computed and plotted in **Figure 10** which shows that Nigeria ES is challenged by sustainability indicating the higher energy consumption per capita and the higher carbon intensity. Furthermore, the country is a leader in competitiveness and supply confirming gas, coal, and oil domination in its energy mix. The diversity of the energy mix of an economy (HHI) represents the level of diversity of the energy mix of an economy and ranges from 0.31 to 1, 0.31 being the most diversified and 1 the more concentrated; only four energy sources (gas, oil, coal, and renewable) have been considered. The index indicates that the energy sector is more concentrated in the ECOWAS with an average HHI of 0.71 and general non-secure.

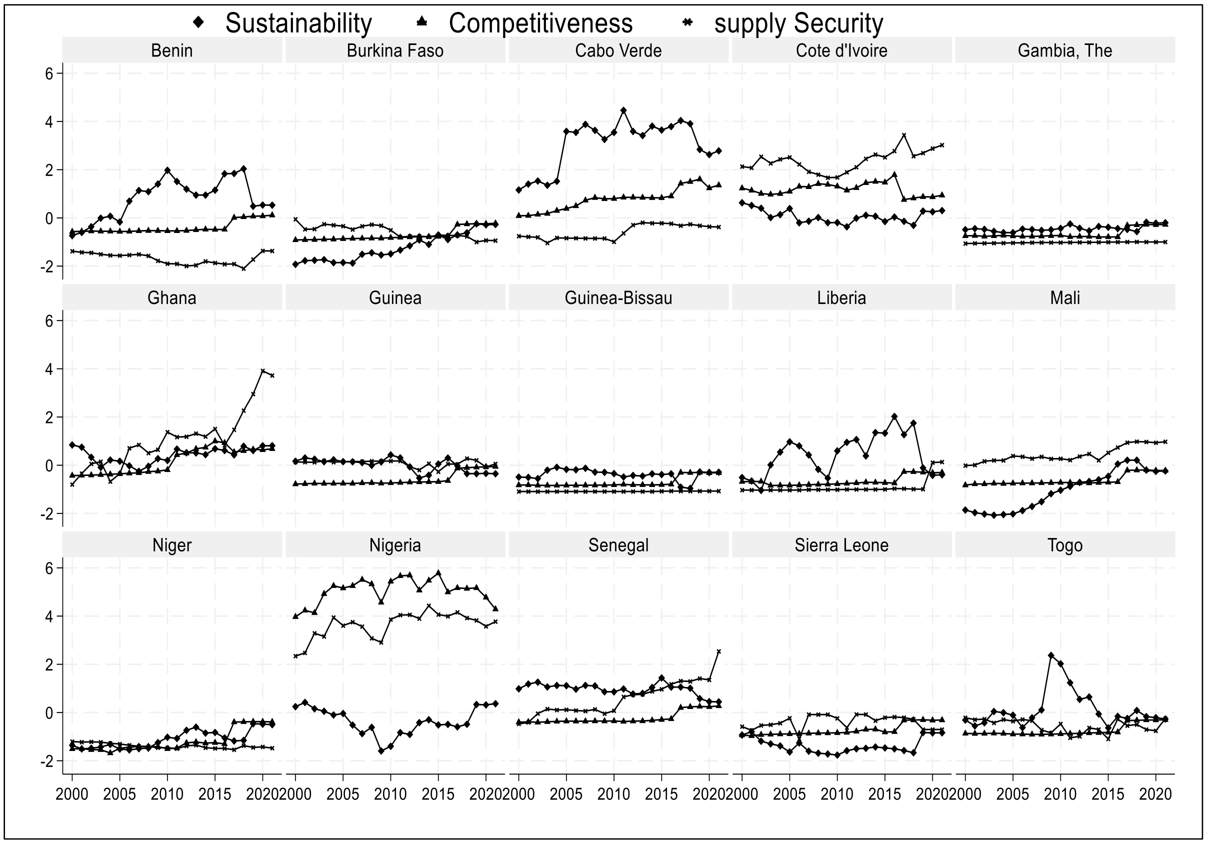

Figure 10: Energy security components graph within ECOWAS countries

RE consumption data are from the International Renewable Energy Agency (IRENA) and include the total renewable energy, hydropower, solar, bioenergy, RE from municipal waste, and biogas consumption in megawatts. **Table 1** indicates that there is a higher standard deviation in total RE consumption in ECOWAS (2416 MW) suggesting a higher heterogeneity between the panel elements along the time confirmed by the minimum zero in the indicator. The different RE sources are introduced to capture their specific impact in the analysis. The additional regressors introduced in our model (Demographic growth, net inflow foreign direct investment (% GDP), consumer price index, and school enrolment, secondary (% gross)) are from WDI while institution factors are from the Worldwide Governance Indicators (WGI). The institutional variables are ranked from -2.5 (low) to 2.5 (high). To facilitate interpretation of the results, we reclassify our variable as follows:-((index+2.5)-5), where 0 represents low institutional quality and 5 is a high level.

Table 1: Data source and descriptive statistics

Variables	Resume	Mean	Std. dev.	Min	Max
Energy efficiency (EF)	**Dynamic Slack-Based Measures**	0.579	0.197	0.243	1
Labor	Input: Total labor force	63.83	8.225	45.49	79.52
Capital	Input: Gross fixed capital formation	19.78	6.790	1.097	52.42
Energy	Input: Total energy consumption	1607	1449	270.0	7693
GDP	Desirable output: Gross domestic product	1052	696.0	356.3	3319
CO2 emissions	Undesirable output: Total GHG emissions	1.312	2.546	0.0100	12.80
Energy security (ES)	**PCA analysis**	1.522	1.346	0	6.140
Sustainability dimension	**ES Dimension 1**	2.47	1.219	-2.072	4.462
Energy per capita	Energy consumption per capita	1607	1449	270.0	7693
Carbone intensity	GHG Emissions (as CO2 equivalent) per GDP	506.2	189.8	47.62	800
Energy intensity	Energy consumption per GDP	0.745	0.246	0.275	1.609
Competitiveness dimension	**ES Dimension 2**	2.57	1.515	-1.678	5.783
GDP per capita	Gross domestic product per capita	1052	696.0	356.3	3319
Coal production	Coal production per capita	5.474	17.80	0	105.1
Oil production	Oil production per capita	797.9	1970	0	10347
Gas production	Gas production per capita	225.1	517.9	0	2585
Security of supply dimension	**ES Dimension 3**	2.38	1.474	-2.102	4.429
Electricity_gas	Electricity from gas	1.539	4.710	0	24.42
Electricity_coal	Electricity from coal	0.0542	0.184	0	0.930
Electricity_ oil	Electricity from oil	0.690	0.935	0	4.880
Energy imports	Energy net imports	0.0663	0.491	-1.840	1.290
HHI	Diversity of the energy mix of an economy	0.728	0.223	0.308	1
Explanatory variables					
RE	Total renewable energy	1244	2416	0	13083
HP	Renewable hydropower	1222	2408	0	13070
Wind	Onshore wind energy	2.531	12.73	0	82.56
SP	Concentrated solar power	10.76	37.18	0	381.4
Bioenergy	Bioenergy	8.783	18.74	0	78.54
Waste	RE from municipal waste	3.835	10.70	0	66.70
Biogas	Biogas	0.023	0.129	0	1
DG	Demographic growth	0.026	0.007	0.008	0.056
FDI	Foreign direct investment	1.884	0.527	0	4.672
P	Consumer price	110.1	50.72	19.21	354.3
HCA	Human capital: school enrolment, secondary	43.06	27.81	1.170	156.4
INQ	**Institutional quality: PCA analysis**	5.467	2.164	0	10.025
Control of corruption	Control of corruption	3.095	0.552	0.373	4.081
Government effectiveness	Government effectiveness	3.319	0.444	2.144	4.292
Political stability	Political stability	3.037	0.830	1.276	4.903
Regulatory quality	Regulatory quality	3.147	0.385	2.226	4.356
Rule of law	Rule of law	3.165	0.539	1.838	4.381
Voice and accountability	Voice and accountability	2.827	0.591	1.526	3.960

1.4.5. Pre-estimation tests and estimation technic

Figure 11 illustrates the analysis framework that summarizes the methodological approach and pre-estimation tests required for the estimation technique validation. Pre-estimation tests include Im–Pesaran–Shin (IPS) unit-root test, collinearity, and multicollinearity test, Breusch-Pagan /Cook-Weisberg test for heteroskedasticity, and Pesaran cross-sectional dependence test. To avoid problems of collinearity in the final model, simple Ordinary Least Squares (OLS) regressions are performed and checked for collinearity and multicollinearity, calculating the centered variance influence factors (VIFs) for the independent variables. If all VIF values are below five, there is no multicollinearity in the data. The results of our set independent variables reported in **Table 2** show an average VIF of 1.7, which means that multicollinearity is not an issue. In addition, all independent variables present VIF values below 5 and range between 3.2 (GDP per capita) and 1.07 (FDI). Therefore, no independent variable is causing the collinearity issue.

Once collinearity and multicollinearity problems are avoided, a test for heteroskedasticity is performed using the Breusch-Pagan / Cook-Weisberg test. The results confirmed the presence of heteroskedasticity in our data panel. We also perform country-specific autocorrelation tests by applying the Pesaran cross-sectional dependence (CD) test. The error cross-section dependence (CD) test for panels with T periods and N individuals is introduced by Im et al. (2003) as:

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N-1}\hat{\rho}_{ij}\right) \tag{1.13}$$

Where $\hat{\rho}_{ij}$ is the average of pair-wise correlation coefficients of OLS residuals from the individual regressions in the panel. If cross-sectional dependence is confirmed, second-generation stationary tests should be used. The test performed in this research suggested the presence of country-specific autocorrelation. To deal with this issue two econometric approach groups can be used such as taking first differences and using a dynamic approach. However, the panel stationarity test perfumed with Im Pesaran Shin unit root gave the precondition of a dynamic approach. Indeed, the results of this test show that all variables are stationary at first difference. To capture both short and long-term effects of all ES and EF indicators we estimate the Panel Auto-regressive Distributed Lags model. The precondition of this model stipulates that all variables are I(0) or stationary at first difference or some variables are I(0) and others are I(1) (as in the current case).

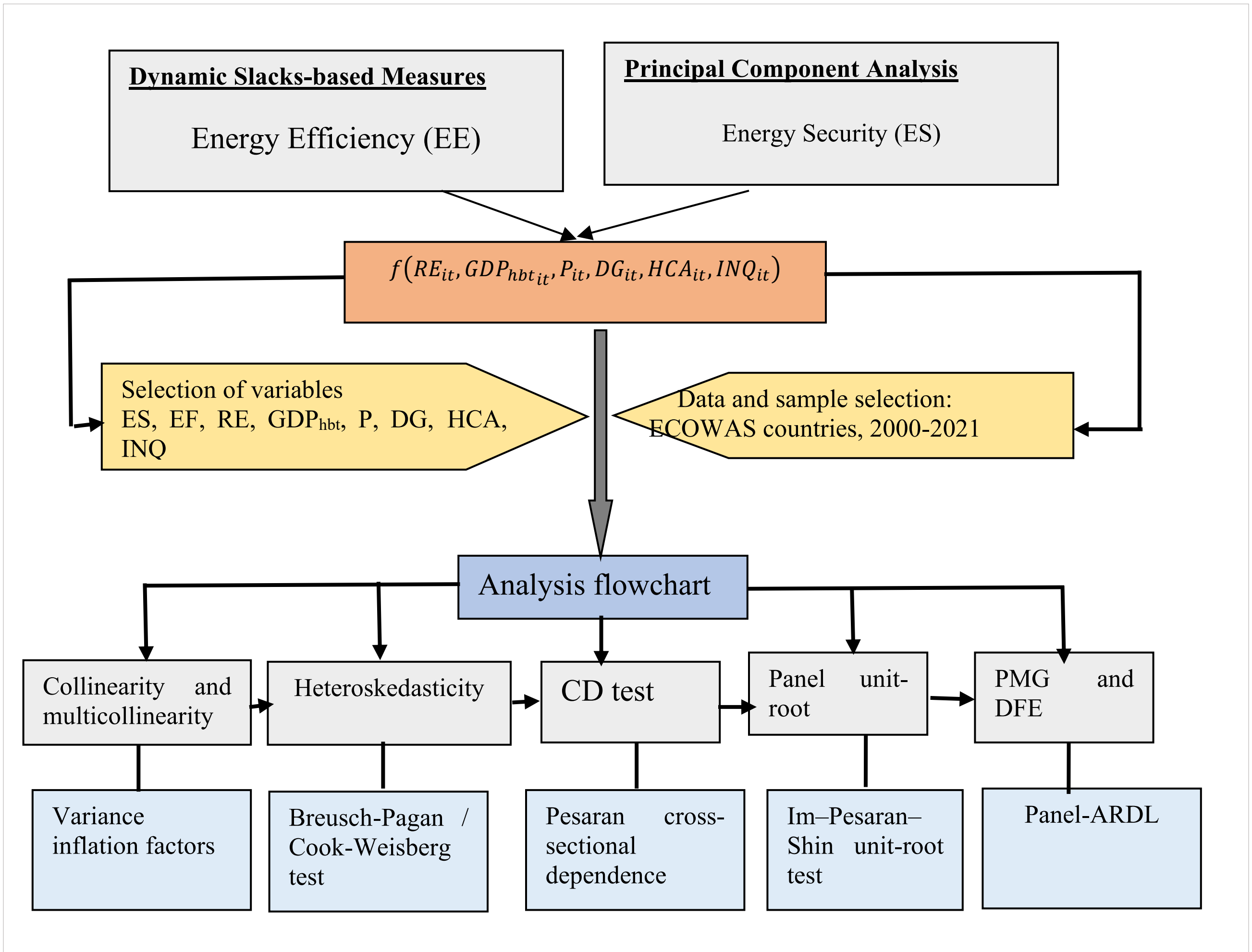

Figure 11: Analysis framework
Source: Authors following Owjimehr et al. (2023)

To examine the long-run relationship between the variables, we have applied a panel autoregressive distributed lag model based on three different estimators: the Mean Group estimator (MG), Pooled Mean Group (PMG), and Dynamic Fixed Effect (DFE). According to Pesaran et al. (1999), an ARDL dynamic heterogeneous panel regression can be written by using the ARDL (p, q) approach where 'p' is the lags of the dependent variable and 'q' is the lags of independent variables. The time t = 1, 2…, 22 and groups i = 1, 2, …., 15, the panel model can be written as follows.

$$e_{it} = \sum_{j=1}^{p} \lambda_{ij} e_{i,t-j} + \sum_{j=0}^{q} \delta'_{ij} X_{i,t-j} + \mu_i + \epsilon_{it} \tag{1.14}$$

Where e_{it} is the ES or EF dependent variable, X_{it} is the $k * 1$ vector of explanatory variables, δ_{ij} are $k * 1$ coefficient vectors; and λ_{ij} are scalar coefficients of the lagged dependent variables. If the variables in the unit root test are, I (1) and cointegrated, formerly the error term is an I(0) process for all panel individuals. A principal feature of cointegrated variables is their responsiveness to any deviation from long-run equilibrium. This feature implies an error correction model in which short-run dynamics of the variables in the system are influenced by the deviation from equilibrium.

Table 2: Data pre-estimation tests

Test Variables	Im–Pesaran–Shin (IPS) unit-root		Collinearity and multicollinearity		Breusch-Pagan / Cook-Weisberg test for heteroskedasticity		Pesaran cross-sectional dependence test	
	At level	First difference					Fixed Effect	Fixed Effect
ES	2.839	-8.792***	dependent	-	Dependent	-	Dependent	-
EF	-3.081***	-	-	dependent	-	dependent	-	dependent
RE	4.491	-6.468***	1.78	1.78	-	-	-	-
GDP/hbt	4.898		3.20	3.20	-	-	-	-
DG	1.132	-3.939***	1.79	1.79	-	-	-	-
FDI	-2.688**	-	1.07	1.07	-	-	-	-
P	10.649	-1.609*	1.15	1.15	-	-	-	-
HCAP	-3.862***	-	1.29	1.29	-	-	-	-
INQ	-0.455	-7.722***	1.65	1.65	-	-	-	-
Model	-	-	1.70	1.70	57.13***	16.00**	2.544*	2.676**

Thus, considering an error correction equation, Equation (1.14) is transformed as:

$$\Delta e_{it} = \emptyset_i\left(e_{i,t-1} - \theta'_i X_{it}\right) + \sum_{j=1}^{p-1} \lambda^*_{ij} e_{i,t-1} + \sum_{j=0}^{q} \delta'^*_{ij} X_{i,t-j} + \mu_i + \epsilon_{it} \tag{1.15}$$

Where, $\emptyset_i = -\left(1 - \sum_{j=1}^{p} \lambda_{ij}\right)$, $\theta_i = \sum_{j=0}^{q} \delta_{ij} / (1 - \sum_k \lambda_{ik})$, $\lambda^*_{ij} = -\sum_{m=j+1}^{p} \lambda_{im}$ $j = 1,2,\dots,p-1$, and $\delta^*_{ij} = -\sum_{m=j+1}^{q} \lambda_{im}$ $j = 1,2,\dots,q-1$.

The parameter $\emptyset_i$ is the Error Correction speed of adjustment term (ECT). If this term is equal to zero, there would be no evidence for a long-term relationship. The term is expected to be statistically and significantly negative under the prior assumption that the variables show a return to long-run equilibrium. All methodological analysis steps are illustrated in the analysis framework (Figure 11).

1.5.Empirical results

Panel-Auto Regressive Distributed Lags (Panel-ARDL) can be estimated by three different estimators the mean group estimator of Pesaran & Smith (1995), the Pooled Mean Group estimator developed by Pesaran et al. (1999), and Dynamic Fixed Effect Estimators (DFE). Following the objective of this paper which is to assess the impact of renewable energy consumption on energy security and efficiency within ECOWAS countries, we estimate Panel-ARDL by two different estimators. The Pooled Mean Group estimator is useful to assess the overall and country-specific impacts for the comparative analysis. The robustness of the overall impact results is checked by estimating the Dynamic Fixed Effect Estimators (DFE).

1.5.1. Model restricted

Equation (1.15) is firstly restricted to a short equation exploring the impact of RES on ES and EE ignoring other factors' effects. The results are compiled in **Table 3** which shows the robust Error-Correction Term (ECT). Indeed, all ECT ranges between -1 and 0, and are statistically significant. The negative and statistically significant error-correction term (ECT) across all RE sources for both ES and EE confirms the presence of long-run convergence, suggesting that any deviation from equilibrium will be corrected over time. This aligns with the findings of Apergis and Payne (2011) and Sadorsky (2009), who also reported long-term adjustments in renewable energy integration within energy markets.

In the short run, the effects of different RE sources on ES and EE vary. Hydropower (HP) and Biogas exhibit marginal short-term positive effects on ES, consistent with Ellabban et al. (2014), who emphasized that hydropower provides a reliable and stable energy supply. However, Total Renewable Energy Sources (TRES) and Waste-to-Energy show negative or insignificant short-term effects, implying that integrating diverse renewable sources into the energy mix requires time before contributing to security and efficiency. Similar conclusions were drawn by Marques et al. (2010), who emphasized that the structural transition towards RE initially faces economic and technical constraints.

In the long run, most RE sources positively contribute to ES and EE, reinforcing the notion that renewable energy investment improves sustainability and self-sufficiency. Solar photovoltaic (SP), Biogas, and Waste-based renewables significantly enhance ES, supporting the arguments made by IRENA (2020) that solar PV is one of the most scalable solutions for achieving energy security. The strong long-term impact of biogas and waste-based energy aligns with REN21 (2021), which highlighted that these sources are crucial in diversifying energy supply, particularly in urban areas. A notable exception is wind energy, which shows an extremely high long-term coefficient for ES

(57.150). This anomaly suggests either a data scaling issue or a structural limitation of wind energy, such as intermittency (see Jacobson & Delucchi, 2011). Furthermore, the negative long-term effect of wind energy on EE indicates that while wind energy contributes to security, its efficiency might be constrained by capacity utilization and storage limitations (Lund, 2007).

Table 3: Model restricted: Impacts of Renewable Energy Sources on Energy Security and Efficiency

	Energy security (ES)				Energy efficiency (EE)			
RE type	ECT	Short term	Long term	constant	ECT	Short term	Long term	constant
TRES	-0.333***	-0.077*	0.259***	0.142	-0.383***	0.010	0.009*	0.196***
	(0.061)	(0.041)	(0.019)	(0.101)	(0.053)	(0.036)	(0.005)	(0.028)
HP	-0.167***	-0.079**	0.319***	0.037	-0.385***	0.002	0.001***	0.196***
	(0.057)	(0.039)	(0.045)	(0.089)	(0.057)	(0.002)	(0.000)	(0.037)
SP	-0.329***	-0.042	0.232***	0.390***	-0.410***	0.008	0.006*	0.230***
	(0.064)	(0.027)	(0.014)	(0.104)	(0.060)	(0.035)	(0.003)	(0.037)
Wind	-0.164***	0.221	57.150	0.360**	-0.358***	-0.009	-0.111***	0.193***
	(0.060)	(0.216)	(54.854)	(0.164)	(0.066)	(0.016)	(0.028)	(0.033)
Bioenergy	-0.227***	0.031	0.021***	0.418***	-0.389***	0.006	0.001**	0.214***
	(0.071)	(0.027)	(0.003)	(0.162)	(0.062)	(0.011)	(0.000)	(0.035)
Waste	-0.218***	-0.313	0.022***	0.408***	-0.353***	0.007	0.047**	0.192***
	(0.067)	(0.316)	(0.004)	(0.155)	(0.066)	(0.010)	(0.021)	(0.040)
Biogas	-0.194***	0.024	0.206***	0.379**	-0.321***	0.021	-2.626	0.183***
	(0.069)	(0.085)	(0.038)	(0.159)	(0.065)	(0.016)	(1.871)	(0.037)

Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Note: TRES: Total renewable energy; HP: hydropower; SP: Solar photovoltaic; Wind: Wind energy; Waste: Renewable energy from municipal waste; ECT: Error-correction term

Different renewable energy sources (RES) significantly increase ES and EE in the long term while it has not generally impacted ES and EE in the short term. The 1 percent increase in total RES (TRES) consumption improves ES by 0.26 and EE by 0.01 in the long term. ECOWAS countries can significantly accelerate their long-term ES and EE by investing in RE.

Especially, countries' investments in hydropower (HP), solar photovoltaic (SP), wind energy, bioenergy, and renewable energy from municipal waste positively and significantly impact the ES and EE in the long term. Indeed, RE production leads to supply diversification, energy price stability, energy independence, or import reduction. These results are in line with the findings of Cergibozan (2022) on hydropower and all renewable energies, while they contrast with solar photovoltaics (SP) in concluding that this source has no significant effect on ES. Apart from supplying security, RE nature is not subject to depletion, and environmental friendliness constitutes the long-term sustainability prerequisite. In addition, according to Savacool et al. (2015) and Moriarty & Honnery (2016), these energy sources are coupled with low technological risk, outperform, and have lower mortality compared to other sources (coal, gas, nuclear, and oil). Ignoring their short-term impacts, different RES capacities to improve ES in the long term within ECOWAS countries can be sorted as HP (0.32), SP (0.23), Biogas (0.21), waste, and bioenergy.

According to the results, the effect of renewable energy consumption on energy efficiency has been positive. In other words, ECOWAS countries at a low level of EE can improve it by expanding renewable energy sources. Based on Lu et al. (2020) and Owjimehr et al. (2023); reducing the proportion of coal and oil consumption in total energy consumption will increase production efficiency, and by increasing the ratio of renewable energies, the energy structure will improve, and along with the improvement of production technology, energy efficiency will also increase.

In the short term, the integration of renewable technologies may incur substantial upfront investment costs, disrupt existing energy supply chains, or reduce grid stability due to intermittent energy sources like solar and wind, resulting in temporary negative impacts (IEA, 2021; REN21, 2023). However, these are often transitional. In the long term, marginal value analysis and scenario-based modeling reveal that these investments lead to significant gains in energy security by diversifying energy sources, reducing reliance on imported fossil fuels, and lowering exposure to global energy price volatility (Stern, 2006; Sovacool et al., 2011). The transmission mechanisms that facilitate this transition include (i) the gradual substitution of fossil-based generation with locally available renewables, (ii) improvements in system efficiency that reduce total energy demand, and (iii) the development of smart grid infrastructure that enhances energy reliability and responsiveness (Awerbuch & Berger, 2003; IRENA, 2017).

1.5.2. Full model: integrating selected control factors of energy security (ES) and efficiency (EE)

The full model is estimated and reported in **Table 4** for ES and **Table 5** for EE. The speed of adjustment reflected by the coefficient of convergence (ECT) is negative and significant in all the fourteen estimators, indicating that there is no omitted variable bias. Integrating other energy security factors does not change the positive impact of different RES and total RE.

The model's results in **Table 4** confirm a positive impact of the total and specific RES consumptions on energy security in the long term, but no significant impact in the short term. In the short term, ES is positively determined within ECOWAS countries by the gross domestic product per capita and negatively associated with institution quality. Consumer price has a consistently positive impact on energy security in the long term, but its impact depends on the renewable energy source. Foreign Direct investment has negative impacts on energy security in the long term. The results reported in **Table 4** suggest that the relationship between GDPs per capita and energy security does not vary timely. With an increase in GDP per capita, investment in the energy sector, especially in high-quality equipment, also increases. With the use of modern technologies associated with supply security, the accidents and depths associated with energy management decrease, and as a result, ES increases.

Table 4: Pooled Mean-Group estimation on Energy Security (ES)

	Pooled Mean-Group estimation on Energy Security (ES)						
VARIABLES	**TRES**	**HP**	**SP**	**Wind**	**Bioenergy**	**Waste**	**Biogas**
Long term							
RE type	0.001***	0.001***	0.143***	0.044	0.095**	0.139***	0.250***
	(0.000)	(0.000)	(0.017)	(0.027)	(0.039)	(0.039)	(0.031)
GDP	0.001***	0.001***	0.000***	0.002***	0.002***	0.002***	0.000**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
DG	28.981***	30.692***	19.868***	-39.425***	-45.117***	-42.543***	19.363**
	(9.295)	(11.576)	(5.891)	(7.679)	(8.456)	(8.127)	(7.598)
FDI	-0.183***	-0.121**	-0.098***	0.045	0.025	0.036	-0.127***
	(0.043)	(0.054)	(0.027)	(0.037)	(0.039)	(0.038)	(0.030)
P	-0.001	-0.001	-0.002***	0.001**	0.002***	0.002***	-0.000
	(0.001)	(0.001)	(0.001)	(0.001)	(0.000)	(0.000)	(0.001)
HCA	-0.000	-0.000	0.000	-0.000	-0.001*	-0.001*	-0.002***
	(0.001)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)
INQ	-0.027	0.100***	-0.013	0.018	0.043*	0.025	-0.035
	(0.023)	(0.036)	(0.021)	(0.021)	(0.023)	(0.021)	(0.023)
Short term							
ECT	-0.405***	-0.292***	-0.524***	-0.409***	-0.403***	-0.410***	-0.353***
	(0.124)	(0.090)	(0.142)	(0.098)	(0.112)	(0.117)	(0.121)
ΔRESs	-0.001	-0.000	-0.071	0.420	-0.022	0.032	0.085
	(0.001)	(0.000)	(0.048)	(0.420)	(0.070)	(0.152)	(0.114)
ΔGDP	0.001***	0.001***	0.001**	0.001**	0.001*	0.001**	0.001*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ΔDG	-68.557	-47.333	-55.805	-27.116	-20.431	-16.018	-61.570
	(60.708)	(41.616)	(47.538)	(58.753)	(50.921)	(45.763)	(43.482)
ΔFDI	-0.093	-0.115	-0.021	-0.072	-0.058	-0.069	-0.018
	(0.170)	(0.166)	(0.129)	(0.135)	(0.144)	(0.133)	(0.112)
ΔP	-0.002	-0.000	0.002	-0.003	-0.002	-0.002	-0.000
	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)	(0.002)	(0.003)

ΔHCA	0.000	0.000	0.000	-0.000	-0.000	0.000	0.001
	(0.001)	(0.000)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)
ΔINQ	-0.060	-0.084**	-0.023	-0.090**	-0.071**	-0.081**	-0.047
	(0.040)	(0.037)	(0.043)	(0.041)	(0.034)	(0.041)	(0.043)
Constant	0.049	-0.261***	0.521**	0.176***	0.162***	0.199***	0.557**
	(0.072)	(0.080)	(0.218)	(0.039)	(0.042)	(0.046)	(0.232)
OBS	288	288	288	288	288	288	288

Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1
Note: TRES: Total renewable energy; HP: hydropower; SP: Solar photovoltaic; Wind: Wind energy; Waste: Renewable energy from municipal waste; ECT: Error-correction term

Table 5: Pooled Mean-Group estimation on Energy Efficiency (EE)

	Pooled Mean-Group estimation on Energy Efficiency (EE)						
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**
VARIABLES	**TRES**	**HP**	**SP**	**Wind**	**Bioenergy**	**Waste**	**Biogas**
Long term							
RE type	-0.000	-0.000	-0.021***	-0.003***	-0.157***	0.001	0.027
	(0.000)	(0.000)	(0.005)	(0.001)	(0.034)	(0.015)	(0.057)
GDP	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
DG	1.654***	1.857***	1.339***	1.517***	2.758***	1.622***	1.598***
	(0.467)	(0.504)	(0.367)	(0.499)	(0.439)	(0.538)	(0.535)
FDI	0.019***	0.018***	0.024***	0.019***	0.021***	0.017***	0.017***
	(0.005)	(0.005)	(0.004)	(0.005)	(0.004)	(0.005)	(0.006)
P	-0.000**	-0.000*	-0.001***	-0.001***	0.000**	-0.001**	-0.001**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
HCA	0.001***	0.001***	0.001***	0.001***	0.001***	0.001***	0.001***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
INQ	0.002	0.001	0.002	-0.001	0.024***	-0.003	-0.004
	(0.005)	(0.005)	(0.004)	(0.006)	(0.005)	(0.006)	(0.005)
Short term							
ECT	-0.419***	-0.433***	-0.515***	-0.401***	-0.407***	-0.459***	-0.456***
	(0.099)	(0.092)	(0.122)	(0.121)	(0.123)	(0.094)	(0.093)
ΔRE	-0.001	0.001	0.008	-0.009	0.007	0.052	-0.000
	(0.001)	(0.001)	(0.032)	(0.007)	(0.032)	(0.046)	(0.004)
ΔGDP	-0.000**	-0.000*	-0.000**	-0.000*	-0.000**	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ΔDG	3.313	1.285	0.796	7.699	-2.690	0.214	1.209
	(8.311)	(8.015)	(12.060)	(12.709)	(9.597)	(8.971)	(8.779)
ΔFDI	0.009	0.014	-0.003	-0.018	-0.004	-0.010	-0.011
	(0.035)	(0.035)	(0.028)	(0.032)	(0.032)	(0.032)	(0.032)
ΔP	0.004**	0.004**	0.004**	0.004**	0.003	0.003*	0.003**
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
ΔHCA	-0.000**	-0.000**	-0.000***	-0.000	-0.000	-0.000**	-0.000**

	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ΔINQ	0.004	0.004	0.002	0.004	0.004	0.004	0.005
	(0.030)	(0.030)	(0.030)	(0.029)	(0.030)	(0.029)	(0.029)
Constant	0.061***	0.084***	0.033	0.078***	-0.030	0.111***	0.117***
	(0.019)	(0.021)	(0.022)	(0.021)	(0.027)	(0.025)	(0.026)
OBS	288	288	288	288	288	288	288

Standard errors in parentheses; *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Note: TRES: Total renewable energy; HP: hydropower; SP: Solar photovoltaic; Wind: Wind energy; Waste: Renewable energy from municipal waste; ECT: Error-correction term

Foreign direct investment (FDI) hurts ES in all RE types considered in the estimation. Taking total RE in the estimation, FDI decreases long-term RE by 0.2 for every unit increase in net investment inflows to acquire a lasting stake in the management of a company operating in an economy other than that of the investor. This relationship is robust for hydropower, solar photovoltaic, and biogas, while it is positive and non-significant for wind, bioenergy, and waste. From a general point of view, analysis of this negative impact draws its basis on the pollution haven hypothesis (Abdul-Mumuni et al., 2023; Bunnag, 2023; Kwakwa et al., 2023; Pata et al., 2023; Udeagha & Ngepah, 2023). FDI can lead to overheating of the economy or inadequate investment, resulting in higher greenhouse gas emissions (Abdul-Mumuni et al., 2023; Kwakwa et al., 2023; Udeagha & Ngepah, 2023). Indeed, this hypothesis is based on the relocation by multinational companies of dirty industries and polluting machinery to developing countries with weak environmental regulations, to reduce their production costs and, in so doing, harm the environment (Adjei-Mantey & Adams, 2023).

Institution quality negatively impacts ES within ECOWAS countries in the short term while they are positively correlated in the long term. This difference sums up the two bodies of institutional theory. In the short term, low institutional quality, according to the functionalist thesis, is a necessary evil for SE. In the long term, however, the opposing corpus of theory sees poor institutional quality as an impediment to market efficiency and the efficient allocation of public goods. This latter body of institutional orthodoxy is made up of the Public Choice school, Information Economics, and New Institutional Economics, all of which reject the Weberian approach of the benevolent despot state, drawn from contract theorists.

In the ECOWAS region, institutional quality exhibits a paradoxical relationship with economic sustainability, with divergent effects over different time horizons. In the short term, weak institutional quality may act as a 'necessary evil' by enabling economic activity to persist in environments where formal institutions are inefficient or inaccessible. This perspective aligns with the functionalist thesis, which posits that informal arrangements and adaptive governance structures can temporarily compensate for institutional deficiencies (North, 1990; Acemoglu and Robinson, 2012). Empirical evidence from West African economies suggests that informal networks, clientelism, and rent-seeking behaviors often fill institutional voids, allowing markets to function despite governance weaknesses (Williams and Horodnic, 2015).

However, in the long term, weak institutions undermine market efficiency and the equitable allocation of public goods, as emphasized by Public Choice Theory, Information Economics, and New Institutional Economics (Buchanan and Tullock, 1962; Williamson, 1985; Stiglitz, 2000). These schools of thought argue that poor institutional quality increases transaction costs, distorts resource allocation, and fosters corruption, ultimately reducing economic growth and deepening structural inequalities. Studies on ECOWAS economies highlight the negative impact of governance deficits on public service delivery, investment climate, and economic diversification (Djankov et al., 2003; Rodrik, 2007).

The long-term consequences of institutional inefficiencies suggest that governance reforms are crucial for sustainable economic development in ECOWAS countries. Strengthening institutional transparency, accountability, and regulatory frameworks is essential to fostering a more resilient and inclusive economic environment. Empirical research underscores the need for policies that improve property rights enforcement, contract stability, and anti-corruption measures to enhance economic performance and social welfare (Kaufmann et al., 2009; Fosu, 2013). Addressing these institutional weaknesses is key to ensuring that economic growth within ECOWAS translates into long-term development and poverty reduction."

Ensuring energy security (ES) is not automatically synonymous with pursuing energy efficiency (EE). Integrating selected additional factors of EE in the Pooled Mean-Group (PMG) estimation illustrated in **Table 5** changes the relationship between RE and EE. Indeed, the results in **Table 5** show that RE does not improve EE and even significantly decreases it when RE is taken as solar photovoltaic, wind energy, and bioenergy. FDI has a positive impact on EE in the long term. This impact is based on the pollution halo hypothesis (Ali et al., 2022; Roy, 2023) is related to the positive impact of FDI on the quality of the environment that occurs either through the augmentation or efficiency effect. The increasing effect is related to the fact that FDI could increase total investment and therefore promote green investment, growth, and social welfare. Green investment in return can improve the share of energy consumption in production decreases, and as a result, energy efficiency increases. The efficiency effect is related to the externalities associated with FDI flows, including the transfer of technology, marketing, and managerial skills capacity which could help in enhancing industry competitiveness and energy efficiency.

In the short term, consumer price is the key EE factor. With a one percent inflation rate within ECOWAS countries, EE increases by 0.004 however this result is potentially related to the consumer monetary illusion being inversed in the long term. Two different types of money illusion can be used to illustrate this result. One of them refers to the time value of money or a tendency to think in terms of nominal rather than real monetary values. Most consumers tend to ignore the time value of their money and just look at what they have in terms of nominal values. The second one is the nominal value of money which affects consumers' perception of real money when they conduct purchases. Human capital assessed as secondary school enrolment contributes to EE improvement in the long term within ECOWAS countries. This control variable can be understood as the country's research and development or population monetary or non-monetary investment in EE capacity significantly increases EE in the long term. The effect of human capital on EE has been positive in all estimations using different RE measures. This result is consistent with Cergibozan, (2022); Gökgöz & Güvercin, (2018) findings concerning the impact of innovation technological changes, and research and development on EE. They suggested that those factors related to human capital are the main drivers of EE in the European Union. The robustness of the results illustrated in **Tables 4 and 5** is checked and reported in **Table 6**. The results using Dynamic Fixed Effect Model (DFE) estimation are consistent with the previous analysis and conclusions.

Table 6: Dynamic Fixed Effect Model (DFE) estimation (Robustness check)

	Dynamic Fixed Effect Model (DFE) with Energy Security (ES)							Dynamic Fixed Effect Model (DFE) with Energy Efficiency (EE)						
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**	**(11)**	**(12)**	**(13)**	**(14)**
VARIABLES	**TRES**	**HP**	**SP**	**Wind**	**Bioenergy**	**Waste**	**Biogas**	**TRES**	**HP**	**SP**	**Wind**	**Bioenergy**	**Waste**	**Biogas**
Long term														
RE type	0.000	0.001***	0.000*	0.001***	0.001***	0.001***	0.001***	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
GDP	0.001***	-27.614*	-22.737**	-28.214*	-25.168*	-26.789*	-28.394*	-0.000	4.533	4.498	4.652	4.960	4.524	4.746
	(0.000)	(14.392)	(11.300)	(15.160)	(13.343)	(13.782)	(15.368)	(0.000)	(4.413)	(4.468)	(4.512)	(4.502)	(4.441)	(4.514)
DG	-27.243*	0.037	0.062	0.053	0.043	0.038	0.047	4.537	0.018	0.015	0.017	0.018	0.013	0.017
	(14.169)	(0.122)	(0.098)	(0.129)	(0.115)	(0.118)	(0.130)	(4.405)	(0.042)	(0.043)	(0.043)	(0.043)	(0.042)	(0.043)
FDI	0.034	0.003*	0.001	0.003*	0.003*	0.003*	0.003*	0.018	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001
	(0.121)	(0.002)	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)	(0.042)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
P	0.003*	0.003	0.002	0.003	0.002	0.002	0.003	-0.001	0.000	0.000	0.000	0.000	-0.000	0.000
	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)	(0.002)	(0.003)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
HCA	0.003	0.033	-0.019	0.032	0.018	0.037	0.029	0.000	-0.063***	-0.063***	-0.062***	-0.062***	-0.060***	-0.063***
	(0.002)	(0.063)	(0.053)	(0.066)	(0.060)	(0.060)	(0.067)	(0.001)	(0.021)	(0.023)	(0.022)	(0.022)	(0.021)	(0.022)
INQ	0.033	0.000	0.145***	0.001	0.195	0.287*	0.008	-0.063***	-0.000	0.004	0.000	0.012	0.070	0.046
	(0.062)	(0.000)	(0.043)	(0.005)	(0.120)	(0.151)	(0.393)	(0.021)	(0.000)	(0.019)	(0.002)	(0.044)	(0.052)	(0.126)
Short term														
ECT	-0.220***	-0.217***	-0.269***	-0.210***	-0.234***	-0.228***	-0.208***	-0.326***	-0.326***	-0.323***	-0.320***	-0.317***	-0.324***	-0.321***
	(0.046)	(0.046)	(0.048)	(0.046)	(0.047)	(0.047)	(0.046)	(0.043)	(0.043)	(0.045)	(0.044)	(0.043)	(0.043)	(0.043)
ΔRE type	-0.000***	-0.000***	0.006	0.002	-0.128*	-0.032	0.180	-0.000	-0.000	-0.012	-0.000	-0.082**	-0.036	-0.025
	(0.000)	(0.000)	(0.027)	(0.003)	(0.068)	(0.075)	(0.156)	(0.000)	(0.000)	(0.014)	(0.001)	(0.033)	(0.037)	(0.077)
ΔGDP	0.001***	0.001***	0.001***	0.000***	0.000***	0.000***	0.000***	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ΔDG	1.792	1.801	2.461	1.956	2.123	2.295	2.056	-0.117	-0.116	-0.126	-0.146	-0.209	-0.090	-0.160
	(3.592)	(3.594)	(3.574)	(3.655)	(3.624)	(3.634)	(3.646)	(1.790)	(1.790)	(1.797)	(1.799)	(1.778)	(1.792)	(1.799)
ΔFDI	-0.016	-0.016	-0.023	-0.020	-0.020	-0.018	-0.017	-0.017	-0.017	-0.017	-0.017	-0.018	-0.017	-0.017
	(0.024)	(0.024)	(0.024)	(0.024)	(0.024)	(0.024)	(0.024)	(0.012)	(0.012)	(0.012)	(0.012)	(0.012)	(0.012)	(0.012)
ΔP	-0.006**	-0.006**	-0.005**	-0.006**	-0.007**	-0.007**	-0.006**	0.002*	0.002*	0.002*	0.002*	0.002*	0.002	0.002*
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
ΔHCA	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ΔINQ	-0.053**	-0.052**	-0.040	-0.049*	-0.044*	-0.046*	-0.048*	0.013	0.013	0.013	0.013	0.015	0.014	0.013
	(0.026)	(0.026)	(0.026)	(0.026)	(0.026)	(0.026)	(0.026)	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)
Constant	0.162	0.164	0.386**	0.177	0.175	0.146	0.183	0.266***	0.267***	0.259***	0.255***	0.246***	0.247***	0.257***
	(0.154)	(0.154)	(0.164)	(0.156)	(0.154)	(0.155)	(0.156)	(0.082)	(0.082)	(0.084)	(0.081)	(0.080)	(0.081)	(0.082)

Standard errors in parentheses; *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Note: TRES: Total renewable energy; HP: hydropower; SP: Solar photovoltaic; Wind: Wind energy; Waste: Renewable energy from municipal waste; ECT: Error-correction ter

1.5.3. Comparative analysis: short-term impacts decomposition by country

The Pooled Mean-Group (PMG) estimation used in this research allows us to highlight countries' specificities in terms of different selected factors' impacts on ES and EE. In the short term, the results performed and illustrated in **Table 7** show that total renewable energy source (TRES) has a positive impact on ES in Burkina Faso and Liberia while a negative impact is observed in Sierra Leone. Burkina Faso and Guinea have some of the lowest rates of electrification in the world, currently standing at 19% and 8% respectively in Burkina Faso and Liberia, with 60% and 34% of urban populations, and almost none in rural areas. Access to clean cooking solutions is also extremely limited throughout the country. Gross Domestic Product (GDP) per capita positively and significantly contributes to ES in Cabo Verde, Guinea, and Senegal.

Demographic growth seems to be an ES challenge factor for Guinea-Bissau, Mali, Niger, and Senegal and a favorable factor in Cabo Verde. The first four countries must integrate their demographic growth rate into ES programs and projects. The pollution halo and haven hypotheses appear in the short term to be related to the country's characteristics. The pollution halo hypothesis suggests that foreign direct investment (FDI) can lead to environmental improvements in host countries, particularly when multinational companies bring in cleaner technologies and better environmental practices. This is often the case when investors originate from countries with strict environmental regulations and corporate responsibility standards. In such contexts, foreign firms tend to transfer greener technologies and contribute to the diffusion of environmentally friendly practices, thereby creating a "halo" effect. For countries like Cabo Verde, which may be more integrated with environmentally conscious foreign partners, this hypothesis could help explain relatively lower levels of industrial pollution despite increased economic activities.

On the other hand, the pollution haven hypothesis posits that countries with weak environmental regulations may attract pollution-intensive industries from more regulated economies. These industries relocate to take advantage of laxer environmental standards, turning the host country into a "haven" for pollution. This dynamic may be particularly relevant in countries like Guinea-Bissau, Mali, Niger, and Senegal if environmental policies are not sufficiently enforced or prioritized in their development agendas. In the short term, such relocations can stimulate industrial growth and job creation, but they may also increase environmental degradation and health risks if not properly managed. Burkina Faso and Nigeria's ES security react face to FDI inflow as additional capital, which leads to an overheating economy or inadequate investment, decreasing ES, while it appears in Senegal as complementary investment for ES improvement. In the rest of the ECOWAS countries, the pollution haven and halo hypotheses do not hold in the short term. Consumer prices negatively impact ES in Cabo Verde and Guinea. Energy efficiency is positively impacted by total renewable energy in Burkina Faso, Côte d'Ivoire, and Mali; GDP per capita in Guinea; demographic growth in Cabo Verde; FDI in Nigeria and Togo; price in Benin, Côte d'Ivoire, Guinea, and Sierra Leone; and institutional quality in Guinea-Bissau.

Different conclusions can be drawn, due to the diversity of country objectives in the energy sector (pursuing ES or EE, or both). Taking the best performer country in ECOWAS between 2000 and 2021 (**Figure 10**), Cabo Verde can ensure its energy consumption by dealing with inflation, quality or adequacy of human capital, and institutional quality, while only the last factor constitutes the challenge for the country to perform in terms of energy use. However, the lower performer (Figure 10), Togo, must integrate investment in energy efficiency (monetary and non-monetary) notions in education.

Table 7: Short-term impact decomposition by country using Full Pooled Mean-Group estimation

VARIABLES	ECT	ΔTRES	ΔGDP	ΔDG	ΔFDI	ΔP	ΔHCA	ΔINQ	Constant
Energy security (dependent variable)									
Benin	-0.198	-0.001	0.001	-35.409	-0.023	-0.003	-0.001	-0.055	-0.085
Burkina Faso	-0.691***	0.001**	-0.000	-39.289	-0.115*	0.007	0.005*	0.070	-0.114
Cabo Verde	-0.398*	0.002	0.001**	73.841**	-0.038	-0.020**	-0.004*	-0.120*	0.059
Cote d'Ivoire	-0.012	-0.000*	0.000	-38.064	0.428	-0.008	0.000	-0.064	0.019
Gambia	-0.115*	-0.005	0.000	0.243	0.031	0.008*	0.000	-0.071***	-0.040
Ghana	-0.069	-0.000	0.000	-112.544	-0.297	-0.005	0.001	-0.291**	-0.231
Guinea	-0.237***	-0.000	0.002***	5.473	0.024	-0.017***	0.003***	0.072**	0.238***
Guinea-Bissau	0.030	-0.019	0.001	-35.555*	0.048	-0.002	-0.000	0.053*	0.011
Liberia	0.084**	0.001***	0.000	3.105***	0.008	-0.000	-0.000*	-0.004	0.003
Mali	-0.412***	0.000	-0.000	-65.890**	0.002	0.007	-0.001	-0.123*	-0.347**
Niger	-0.388**	0.001	0.003	-229.067***	-0.013	-0.003	0.001	-0.067	-0.174
Nigeria	-0.001	0.000	0.001	251.304	-2.315***	-0.001	0.001	-0.480*	-0.019
Senegal	-1.366***	0.001	0.003***	-836.750***	0.740**	-0.011	0.000	0.083	0.787*
Sierra Leone	-1.359***	-0.002***	0.000	25.129	0.053	0.009	0.000	-0.007	0.421
Togo	-0.937***	0.000	0.001	5.117	0.069	0.010	-0.001	0.110	0.201
Energy efficiency (dependent variable)									
Benin	-0.378***	-0.004	-0.001	-34.834	0.011	0.013*	0.000	0.079	0.019
Burkina Faso	-0.176	0.001*	-0.000	22.643	-0.027	0.004	0.001	0.017	0.034
Cabo Verde	0.110	0.001	-0.000	69.050**	0.003	-0.003	-0.001	-0.166***	0.026
Cote d'Ivoire	-0.565***	0.000**	0.000	-11.448	-0.019	0.016**	0.000	0.023	0.069
Gambia	-0.193	-0.009	-0.001	-22.346	0.020	-0.005	-0.000	-0.049**	0.055
Ghana	-0.393*	-0.000	0.000	5.807	-0.054	-0.003*	-0.001	-0.014	0.092*

Guinea	-0.430***	-0.000*	0.001***	-15.847***	-0.018***	0.006***	-0.001***	0.003	-0.025
Guinea-Bissau	-0.699***	-0.007	-0.002	-57.230	0.240*	0.015	-0.001	0.332***	0.239**
Liberia	-1.519***	-0.000	0.000	-1.171*	-0.012**	0.001	-0.001***	0.036***	0.139
Mali	-0.166***	0.000***	-0.001	10.726	-0.036	0.003	-0.001***	-0.001	0.001
Niger	-0.146**	0.001	-0.001*	-0.599	-0.056**	-0.003*	0.000	-0.019	0.032*
Nigeria	-0.194	-0.000*	0.000	26.033	0.374***	-0.001	-0.001	0.066	0.048
Senegal	-0.754***	-0.000*	-0.000*	33.338	-0.151***	0.002	-0.000*	-0.011	-0.010
Sierra Leone	-0.573***	-0.001*	0.000	42.391	-0.155***	0.008**	0.000	-0.200	0.174**
Togo	-0.202	0.000	-0.001	-16.825	0.022*	0.002	-0.001***	-0.037	0.019

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Note: TRES: Total renewable energy; ECT: Error-correction term

1.5.4. Overview of the case of Togo

Energy efficiency analysis showed that Togo is a less performer country compared to its counterparts in ECOWAS. In addition, the transition to cleaner and renewable energy in Togo is progressing slowly due to unfavorable socioeconomic, demographic, and spatial factors that favor traditional fuel use over clean and efficient energy (WHO, 2014). Togo's energy consumption primarily comes from biomass, petroleum products, and electricity (SEI-Togo, 2017). Households account for 74% of this consumption. Biomass is sourced internally and unregulated, petroleum is entirely imported and mainly used in the transport sector and for electricity generation. Electricity generation in Togo is composed of 50.6% oil, 49% hydro, and 0.4% biomass combustion. Togo's reliance on non-renewable energy is significant. A specific overview of the impact of renewable energy on energy efficiency and security is an interesting case.

Nevertheless, 23 years after signing the United Nations Framework Convention on Climate Change (UNFCCC), Togo has committed to the Paris Agreement under COP21 to reduce non-renewable energy consumption and promote sustainable energy. Togo's national energy policy, as outlined in the National Development Plan, aims to ensure universal access to clean energy by 2030 and achieve 50% renewable energy capacity by 2025, increasing production from 34.7 MW to 264.7 MW. To finance this ambitious program, the Togolese government has sought national and foreign private investments. Togo has become an attractive destination for FDI in recent years due to numerous reforms that have improved the business environment (UNCTAD, 2021). According to the World Bank, Togo was the leading reforming country in Africa and the third globally in 2020. FDI in Togo increased by 85%, from $346 million in 2019 to over $639 million in 2020, despite the global recession caused by the COVID-19 pandemic. Togo ranks first worldwide in attracting FDI relative to the size of its economy, with a score of 10.83 on the Greenfield FDI Index. FDI in Togo is primarily directed towards industrial, infrastructure, and financial projects.

Recently, the government has launched several public-private partnerships (PPPs) with foreign investors to achieve its ambitious energy mix goals. Since 2018, Togo has initiated two major renewable energy projects through PPPs. The "Kékéli Efficient Power Plant" is a joint venture between the Eranove Group (75%) and the government (25%), costing $145.6 million. This 25-year PPP includes Siemens and TSK and aims to provide renewable energy to over 250,000 households, impacting 1.5 million people. The second project is the "Sheikh Mohamed Bin Zayed" solar power plant, the largest solar photovoltaic power plant in West Africa, launched in 2021. Located in the central region of Togo, this PPP grants Amea Power a 25-year operation contract for a total cost of $60 million. The plant is expected to generate approximately 90,255 MWh of energy per year, ensuring access to electricity for 158,333 households. Additional solar power projects and solar kit provisions are underway in other regions through PPPs, thanks to FDI. Enhancing the impact of different energy policies on the Togolese economy and understanding households' attitudes toward renewable energy adoption and energy efficiency investment appear to be critical to the country’s energy sustainability.

1.6. Conclusion and policy implications

This chapter aimed to assess the impact of renewable energy consumption on energy security and efficiency within ECOWAS countries. We employ the non-parametric method using the dynamic DEA technique and ARDL estimation on World Bank, Our World in Data, and WGI panel data from 2000 to 2021 to this end. The results show that ECOWAS countries are currently experiencing a low EE (0.58), and the growing consumption of renewable energy is positively impacting the ES and EE of the community in the long term. Furthermore, this impact is more pronounced and sorted as Hydropower, Solar Photovoltaic, and Biogas. This suggests that supporting the energy transition in ECOWAS countries is an important pillar for improving EE and ES. The high energy efficiency rate is observed in Cabo Verde, which can ensure its energy consumption by dealing with inflation, quality or adequacy of human capital, and institutional quality, while only the last factor constitutes a challenge for the country to perform better in terms of energy use. However, the lower performer, Togo, must integrate investment in energy efficiency (monetary and non-monetary) notions in education.

This research sheds light on the importance of considering the country's specificities in implementing ES and EE policies. Therefore, further research can focus on implementing pro-environmental policies likely to improve RE consumption and household willingness to invest in energy efficiency. These policies could include reducing the cost of lending to renewable energy projects, cutting taxes, and working with neighboring countries to exchange best practices, share experiences, and build capacity in the use of clean, environmentally friendly energy technologies.

Chapter 2: RENEWABLE ENERGY ADOPTION INTERACTION WITH HOUSEHOLDS' INVESTMENT IN ENERGY EFFICIENCY IN TOGO

Abstract

Renewable energy (RE) and energy efficiency (EE) are integral to sustainable energy policies and a green economy. Nevertheless, their integration within residential buildings often occurs in isolation in developing countries. This research assesses the interplay and impact of RE adoption on households' investments in EE, analyzing data from 462 households in Togo's Centrale region. An endogenous switching probit model was employed to optimize the households' discounted sum of instantaneous utilities of energy consumption. The findings indicate that the adoption of clean energy prompts households to enhance their EE investments both monetarily and non-monetarily. Factors such as subjective life satisfaction, homeownership, age, sedentary lifestyles, and environmental attitudes significantly increase the probability of households adopting RE or investing in EE. In formulating incentive policies for RE and EE, it is essential to consider the energy sustainability of households. Advocating for net-zero-energy buildings through simultaneous investments in EE and RE will facilitate exclusive reliance on renewable energy sources. As Togo's economy advances, it is anticipated that residents' satisfaction and willingness to invest in RE and EE will grow.

Keywords:

Energy transition, renewable energy, energy efficiency, energy-saving behavior, synergy, sustainability.

2.1. Introduction

Even though household energy efficiency (EE) and renewable energy (RE) adoption constitute the two pillars of sustainable energy policy for the green economy, the related policies, programs, and research generally grow separately (Dato, 2017; Ollier et al., 2020; Prindle et al., 2007). However, aligning household energy efficiency (EE) and renewable energy (RE) initiatives can lead to significant benefits. By integrating EE and RE programs, policymakers can create a more holistic approach to sustainable energy, maximizing these initiatives' overall impact and effectiveness. This alignment can result in reduced energy consumption, lower greenhouse gas emissions, and greater cost savings for households and businesses alike. Efficiency is key to slowing energy demand, so increasing the supply of clean energy can significantly reduce the use of fossil fuels (Ollier et al., 2020). Through incentivizing consumers to invest in both energy areas, there is an opportunity to reduce overall energy demand and CO2 emissions. When consumers are informed and motivated to make energy-efficient choices, such as upgrading to energy-efficient appliances or improving home insulation, they can significantly reduce their overall energy consumption. Similarly, when consumers choose to invest in renewable energy options like solar panels or wind turbines, they contribute to a cleaner energy grid and help lower dependency on fossil fuels. The residential sector is one of the most energy-intensive sectors around the world, and thus a focal point for reducing greenhouse gas emissions associated with energy consumption (Solà et al., 2020).

In Africa, energy is 60% consumed by residential buildings (IEA, 2020). It accounts for 70% of Togo's energy consumption with an energy efficiency of 29.5% (Togo Energy Situation, 2017). In addition, Togo's total energy consumption is divided into 4% electrical energy, 20% petroleum products, and 76% biomass. A large part of this energy is consumed by households (68.3%), followed by the transport sector (16.1%), commercial and public services (10.2%), and industry (5.3%) (IRENA, 2020). Households use mainly wood as a direct form of energy (56.9%) and charcoal (33.7%). Nevertheless, the Economic Community of West African States has placed a high priority on the development of renewable energy sources (). The organization has set ambitious targets to increase the share of renewable energy in the region's energy mix, aiming for 10% by 2020 and 20% by 2030. This commitment demonstrates the recognition of the potential of renewable energy to address energy security, climate change, and sustainable development challenges in the region.

Furthermore, by deciding to invest in energy-efficient technologies, households can reduce the amount of energy used to obtain the same service, thus saving energy (Charlier, 2015; Tovar, 2012; Trotta, 2018). They can also accelerate energy sustainability by adopting renewable energy (Kansongue et al., 2022). However, operating on both energy issues is a necessary and synergistic measure to decarbonize energy systems and reach the temperature goals of the Paris Agreement (Ollier et al., 2020). In addition to reducing energy consumption, adopting renewable energy sources can also lead to significant cost savings for households in the long run. By generating their electricity through solar panels or wind turbines, households can reduce their dependence on the grid and potentially even sell excess energy back to the utility company, creating an additional source of income. Furthermore, renewable energy systems require minimal maintenance and have a longer lifespan compared to traditional energy systems, resulting in lower maintenance and replacement costs for homeowners. Indeed, conceptually and theoretically, there is a certain synergy between RE adoption and EE (Dato, 2017). Conceptually, investing in EE and adopting RE stimulates temporal, economic, and geographical synergies (Prindle et al., 2007). For example, "Solar Energy for All" (San Francisco), and "Energiesprong" (Netherlands) initiatives not only help households save on their energy bills but also transform homes into sustainable and affordable living spaces.

Economically, the combination of RE and EE policies can reduce overall power system costs, stabilize energy prices, generate investment, and stimulate economic activity compared with a policy focused solely on renewables (Prindle et al., 2007). For energy use dynamics, efficiency offers significant savings in the short and medium term, but RE provides opportunities that increase over time. Indeed, even if non-renewable energy possibilities are not exploited aggressively and inefficiently, they will be limited in the long term due to their exhaustible nature. Furthermore, the non-uniform geographical distribution and availability of certain renewable energies are complemented by their efficient use, smoothing out regional differences between states and facilitating national consensus-building. However, household decisions to invest in EE and green energy have been pursued on separate tracks.

Theoretically, household decisions to invest in clean energy have been investigated based on a conflictual debate between real and hypothetical behaviors (Atalay et al., 2016; Khalid et al., 2021; Salim & Rafiq, 2012; Upton & Snyder, 2015; Viardot, 2013; Wall et al., 2021). However, relying solely on a conflictual debate approach may have limitations in understanding household decisions to invest in clean energy. This approach often overlooks the complex interplay of various factors such as social norms, financial constraints, and environmental consciousness, which can greatly influence individual choices. Moreover, it fails to capture the interactive nature of decision-making processes and the potential impact of RE on EE. The latter, based on stated preference methods, rely on households' willingness to adopt or pay for renewable energies (Liu et al., 2013; Sardianou & Genoudi, 2013). However, studies relying on the real behavior of consumers investigate how clean energy adopters react according to different financing mechanisms. The theory of uncertainty among consumers in the context of energy savings, energy price fluctuations, and the irreversibility of investment provides insight into the risk-averse nature of increasing investment in energy efficiency (Hirst & Brown, 1990). Conceptually, the two decisions can be jointly determined by several factors. Based on the expanded Theory of Planned Behavior (TPB), previous studies have shown that perceptions of self-efficacy, environmental concerns, awareness of renewable energy, and beliefs about its benefits facilitate the adoption of renewable energy (Wall et al., 2021).

Taking energy efficiency investments as the monetary or financial, and non-monetary (curtailments) investments required to reduce overall energy consumption, the literature underlined some common factors affecting renewable energy adoption. Those factors are social, economic, demographic (observable), or environmental motivations (unobservable). Despite this synergetic relationship that has been theoretically demonstrated by maximizing the discounted sum of instantaneous household utilities (Dato, 2017; Ekholm et al., 2010) and empirically illustrated (Dato, 2017). Further research on this interaction is needed to enhance sustainable energy policy. Thus, the research question of this paper is: What is the interaction of renewable energy adoption with households' investments in energy efficiency?

This research aims to assess renewable energy adoption (hydropower, solar power) interaction (synergy and impact) with energy efficiency (monetary and curtailments) investment for Togolese households. We consider both types of energy conservation actions, namely monetary investments (acquisition of new technologies, low-energy, or high-efficiency appliances) and curtailments (investments in behavioral change such as scheduling, turning off lights, reducing heating or air conditioning, and standby power). Energy efficiency receives particular attention from policymakers, who recognize its important role in improving energy security and affordability. Indeed, Togo adopted ECOWAS's energy efficiency policy, which aims to meet energy efficiency standards for all new private buildings and to improve energy efficiency in industry by up to 30%. In addition, several programs and projects have been launched in Togo focusing on increasing the share of renewable energy in total energy consumption. Not exhaustively, the construction of a 50 MWp solar power plant in Blitta; a 65 MWp plant in Kékéli; the project to supply and install solar kits for households with a high poverty index in the Savanes region (ASHDEN), "CIZO" project are renewable energy initiatives within the country. However, although this regional policy dovetails with the ECOWAS Renewable Energy Policy, at the national level, the synergy between the two still needs to be improved.

Compared to Khalid et al. (2021), Wall et al. (2021), Atalay et al. (2016), Upton & Snyder (2015), Abdmouleh et al. (2017), Dato (2017), and Ollier et al. (2020) studies, this paper contributes to the energy transition literature by addressing energy efficiency as well as accelerating the transition to clean energy in energy energy-importing country with low and poor energy access. Indeed, Togo's main source of energy is electricity, with an increased access rate (from 17% in 2000 to 45% in 2018). However, there are large differences between urban (88.8%) and rural areas (8%). In addition, previous studies dealing with the potential synergies between EE and RE adoption ignored the potential impact of adopting RE on EE (Dato, 2017).

We, therefore, analyze not only the synergetic relationship but also assess the impact of adopting clean energy sources on energy efficiency investments. Furthermore, we analyze households' energy-saving behavior to enhance different factors on energy demand reduction at the residential level. This research examines, therefore, the interplay between renewable energy (RE) adoption and households' investments in energy efficiency (EE) using data from 462 households in Togo's Centrale region. An endogenous switching probit model was applied to optimize the households' discounted sum of instantaneous utilities from energy consumption. The findings reveal that the adoption of clean energy motivates households to increase their investments in energy efficiency, both financially and through non-monetary means.

The remainder of this chapter is organized as follows: Section 2 describes some statistics on renewable energy adoption and energy consumption in Togo; Section 3 reviews the literature on renewable energy adoption interaction with households' investment in energy efficiency; Section 4 details the materials and methods used to achieve the chapter's objectives; Section 5 presents and interprets the empirical results and their econometric analysis; and the conclusion follows in Section 6.

2.2. Current situation on renewable energy adoption and energy consumption in the Togo residential sector

The residential energy sector in Togo plays a critical role in the country's sustainable development and socioeconomic progress. As the nation seeks to balance energy access with environmental sustainability, renewable energy, particularly solar power, has emerged as a promising solution. However, despite government initiatives and international support to expand energy access, adopting renewable energy within Togo's residential sector remains limited. With nearly half of the population still lacking reliable access to electricity and rural households heavily dependent on traditional biomass sources, energy security and environmental sustainability are pressing challenges.

This section examines the dynamics of renewable energy adoption and energy consumption patterns in Togo's residential sector, highlighting the socioeconomic, infrastructural, and policy factors influencing energy use. The findings provide a foundation for understanding the impact of renewable energy adoption on energy consumption patterns and offer insights into strategies for enhancing energy access and sustainability within Togo's residential sector.

2.2.1. The proportion of the population with access to electricity and energy intensity in Togo

Figure 12 highlights important trends regarding energy access and efficiency within the economy, showing both progress and areas where further development is needed. The two key indicators offer insights into how energy accessibility and efficiency have evolved over the past two decades. First, examining electricity access, there is a clear and steady upward trajectory in the proportion of the population that has access to electricity. In 2000, only 9% of the population had access to electricity, a number that grew incrementally each year, reaching approximately 45.4% by 2021. This growth signifies significant improvements in infrastructure and government or private sector efforts to extend electricity networks to more regions. Despite this upward trend, by 2021, less than half of the population had access to electricity. This remaining gap underscores the need for continued investments and policies aimed at achieving universal electricity access, which is crucial for sustainable development and poverty reduction.

The second indicator, Total Energy Supply per GDP PPP, reflects the energy intensity of the economy, essentially measuring how much energy is required to produce each unit of economic output. In 2000, the energy intensity was 10.61, meaning that for every unit of economic output, a certain amount of energy was consumed. Over the years, this figure has generally declined, reaching 8.6 in 2021. This reduction in energy intensity implies that the economy has become more energy-efficient, using less energy for each unit of GDP. Greater energy efficiency can result from technological advancements, shifts towards renewable energy sources, improvements in energy-saving practices, or structural changes in the economy, such as a move towards less energy-intensive industries. This efficiency gain reflects positively on environmental sustainability, as it suggests a decrease in the carbon footprint per unit of GDP.

However, this metric does not show a perfectly smooth decline; instead, there are notable fluctuations, particularly around 2009 and 2010, when energy intensity reached 13.02 and 12.3, respectively. These peaks may be associated with specific economic or energy supply events, such as changes in energy sources, shifts in industrial activity, or other macroeconomic factors that temporarily increase the amount of energy consumed relative to economic output. Such variations highlight the complexities of energy consumption and the impact of external factors, such as global oil prices, economic downturns, or the availability of alternative energy sources, on national energy efficiency.

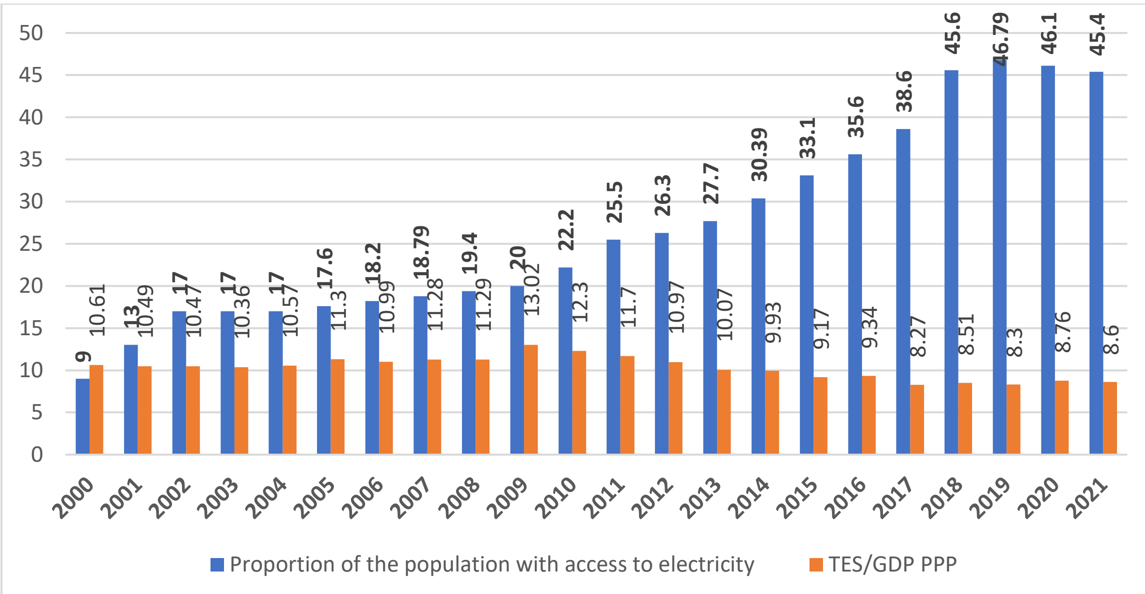

Figure 12: Proportion of the population with access to electricity and energy intensity in Togo
Data source: World Bank, 2024

The dual goals of expanding electricity access and enhancing energy efficiency will be critical as the country seeks to balance economic growth with environmental sustainability. Universal electricity access supports human development and reduces poverty, while energy efficiency aligns with climate goals by reducing emissions per unit of GDP. Together, these trends underscore a pathway towards a more inclusive and sustainable energy future, although they also highlight areas where further investment, technological innovation, and policy support are needed to meet ambitious development and sustainability targets.

2.2.2. Share of modern renewables in Togo

Figure 13 shows the share of modern renewables in Togo from 2000 to 2021. This metric reflects the percentage of renewable energy sources in the country's total energy mix, such as solar, wind, and possibly hydroelectric. Over the two-decade span, the share of modern renewables fluctuates rather than following a steady trend. In 2000, the share of renewables was 11.03%. Small increases were observed in the early 2000s, reaching 12.39% in 2007. This indicates initial efforts to incorporate renewable energy into the energy mix. However, between 2009 and 2010, there was a dip to around 10.25% and 10.16%, suggesting a temporary decline in renewable energy usage. This decline may have resulted from various factors, such as increased reliance on non-renewable energy sources, economic challenges, or shifts in energy policy during those years.

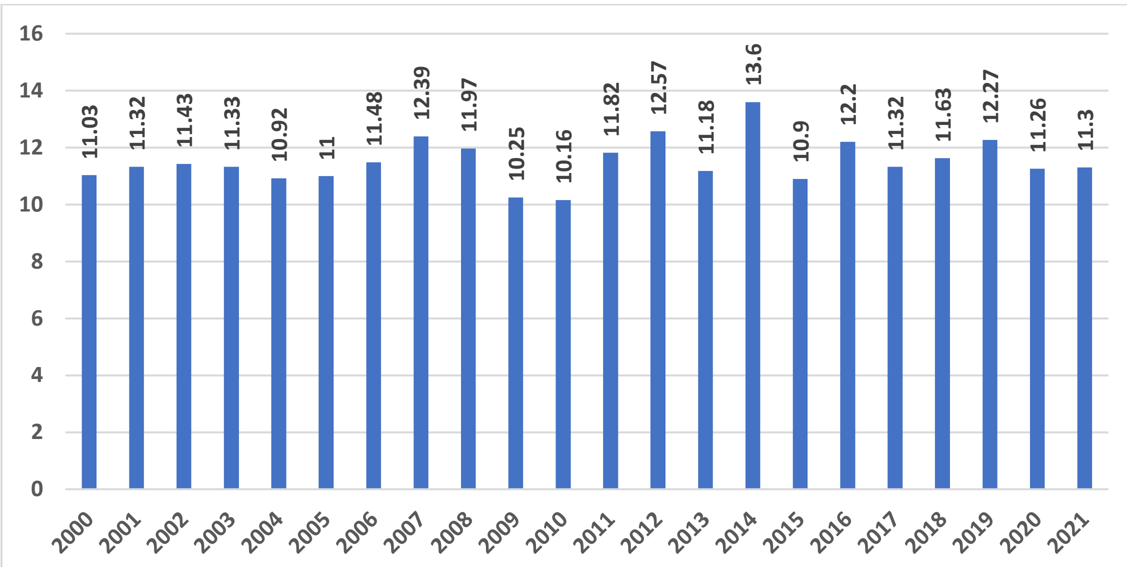

Figure 13: share of modern renewables in Togo
Data source: Our World in Data, 2024

After 2010, there were signs of growth, with the share reaching 13.6% in 2014, the highest level in the dataset. This peak likely reflects an increased focus on renewables, possibly due to government policies or international support for renewable energy projects. However, following this high point, the share of renewables fluctuated again, dipping to 10.9% in 2015 before recovering to a moderate level. By 2021, the share was around 11.3%, close to the values seen at the beginning of the period. The lack of a clear upward trend suggests that while Togo has made some strides toward renewable energy adoption, the transition has not been consistent. Factors such as policy changes, economic constraints, and reliance on other energy sources likely impacted the share of renewables in the energy mix over the years. The fluctuation may also reflect infrastructure and investment challenges that can impede the steady adoption of renewable technologies. The figure shows an inconsistent trend in Togo's adoption of modern renewables, with some growth but also periods of decline. Despite intermittent increases, renewable energy's share remains relatively modest, indicating a need for sustained policy and financial support to achieve a more significant and stable integration of renewables into Togo's energy portfolio.

2.2.3. Energy consumption in Togo

2.2.3.1. Share of total final consumption (TFC) by sector

The data on Togo's Total Final Consumption (TFC) from 1990 to 2022 reveals critical insights into the country's energy consumption patterns across various sectors: transport, industry, residential, and commercial/public services (**Figure 14**). Over the years, the dominance of the residential sector in Togo's energy consumption has been a key characteristic, reflecting the country's energy priorities and the structure of its economy. In the early 1990s, the residential sector commanded more than 70% of TFC, peaking at 79.1% in 1993. This dominance can be attributed to the high household energy demand, which often outstrips the other sectors. This indicates that a significant portion of the population relied heavily on traditional energy sources for cooking, lighting, and other household activities. The high residential share reflects the energy demands of a largely domestic-focused economy, with limited energy-intensive industrial activity and a relatively small commercial sector at that time.

However, over the years, there has been a notable shift in the structure of TFC, with other sectors, particularly transport, gaining prominence. The transport sector, which initially maintained a moderate share, experienced significant growth in the late 2000s, reaching a peak of 30.9% in 2009. This dramatic increase in transport share signals important changes in Togo's economy, such as the expansion of transportation infrastructure, growth in vehicle ownership, and potentially higher economic activity necessitating increased mobility. The rise of the transport sector's energy share could also suggest a shift in Togo's economic landscape, where urbanization, improved road networks, and the movement of goods and services became more critical. This increase likely reflects increased fuel consumption for transportation, raising considerations around energy sustainability, fuel efficiency, and carbon emissions as the sector's demand for fossil fuels grows.

The industry sector, in contrast, has displayed relatively low but fluctuating shares over the years. There are periods, such as 1999 (8.1%) and 2014 (7.4%), where industrial energy consumption increased, which might be associated with specific phases of industrial development or government policies to stimulate industrial growth. Despite these occasional increases, the industry sector's share in TFC has generally remained modest compared to the residential and transport sectors. This trend underscores the limited industrialization in Togo or potentially energy-efficient industrial processes that do not require substantial energy inputs. The relatively low industrial share might also reflect Togo's economic structure, where agriculture and services play a larger role compared to manufacturing or heavy industry. The modest energy consumption in the industrial sector indicates that industrialization has not yet reached levels seen in more energy-intensive economies, possibly due to financial, technological, or infrastructural limitations.

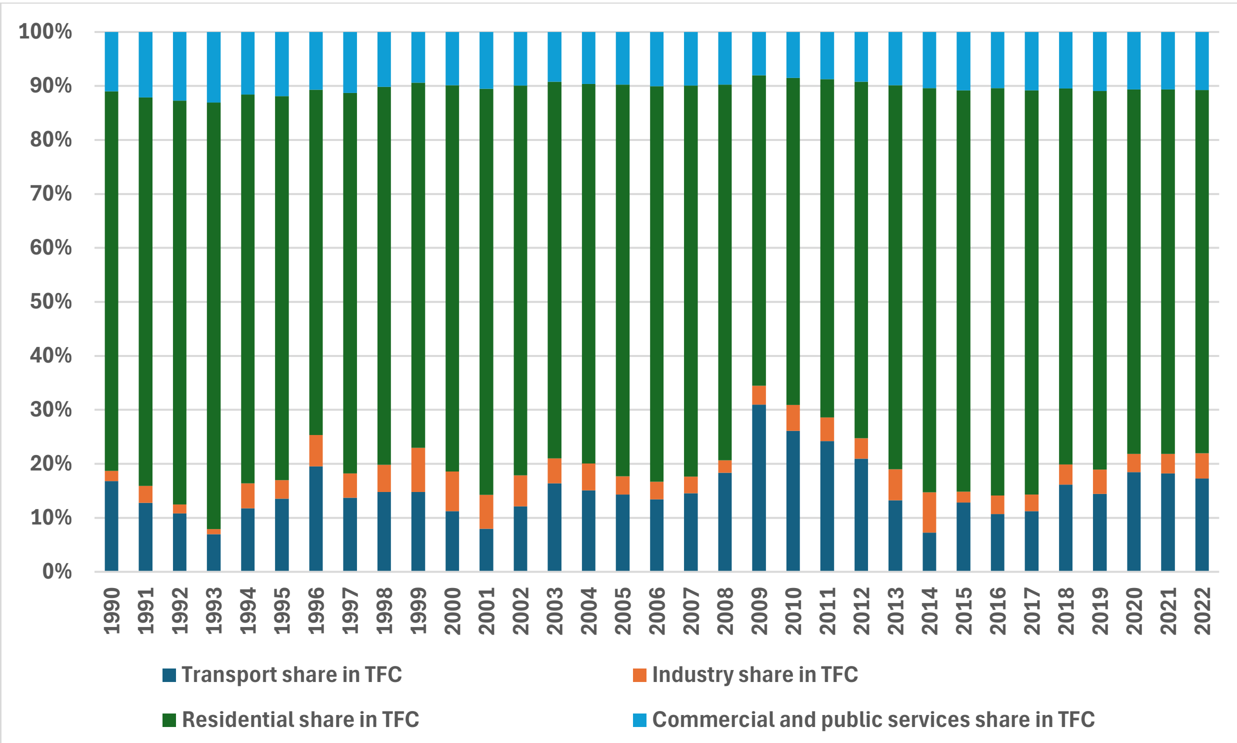

Figure 14: Share of total final consumption (TFC) by sector in Togo
Data source: International Energy Agency, 2024

The commercial and public services sector has maintained a fairly consistent share, around 10% of TFC, over the period. This stability suggests a steady but limited demand for energy within commercial and public services. While there are slight fluctuations, the sector’s share does not display any large upward or downward trends, implying that the energy needs in this area have grown at a steady pace, likely in line with Togo’s gradual economic growth and urbanization. The stability of this sector's share in TFC also suggests that energy policies or infrastructural developments have neither greatly expanded nor reduced energy requirements in this sector. It could reflect the ongoing importance of commercial activities and public services that support urban and rural populations, such as schools, hospitals, and retail services.

Overall, the evolving composition of Togo's TFC reveals a gradual diversification from a residentially dominated consumption pattern to a more balanced demand across residential, transport, and other sectors. While residential consumption remains high, the rise in transport's share points to a shift in priorities, likely driven by growing economic activities that require enhanced mobility and transportation infrastructure. This trend in transport underscores the need for policies that address fuel efficiency and explore alternative, sustainable modes of transportation, especially as the transport sector's reliance on fossil fuels could impact Togo's environmental footprint.

In addition, while the industry sector's energy share is relatively low, there are occasional spikes that hint at the potential for future industrial growth. For sustainable development, this industrial growth should ideally incorporate energy-efficient technologies and possibly renewable energy sources, reducing the risk of heavy dependency on fossil fuels. The commercial and public services sector's steady demand further supports the idea of a balanced energy consumption landscape, which has been essential in supporting both the public infrastructure and service industries. Togo's future energy strategy might focus on addressing the growing demands of transport, improving residential energy efficiency, and supporting the industrial sector's growth through sustainable practices, thereby ensuring a balanced and sustainable energy framework aligned with economic growth and environmental considerations

2.2.3.2. Residential total final consumption (TFC) by source

The data presented provides insights into the trends in residential Total Final Consumption (TFC) by energy source in Togo from 1990 to 2022, specifically in terms of oil products, biofuels and waste, and electricity (**Figure 15**). This breakdown offers a view into how the residential energy mix has evolved, reflecting shifts in energy accessibility, affordability, and possibly policy directions.

The consumption of oil products shows considerable fluctuations across the years. Starting with a low of 791 units in 1990, it declined in the early 1990s, notably dropping to 310 in 1993. This decrease may reflect limited availability or high costs of oil products, as well as potential government regulations or shifts in household preference towards biofuels. From the late 1990s onward, oil consumption generally trended upward, with significant peaks, such as in 2003 (2,766) and 2016 (3,484). However, there is a marked drop again in some years like 2015 (1,126), indicating potential volatility in access or demand for oil products within the residential sector.

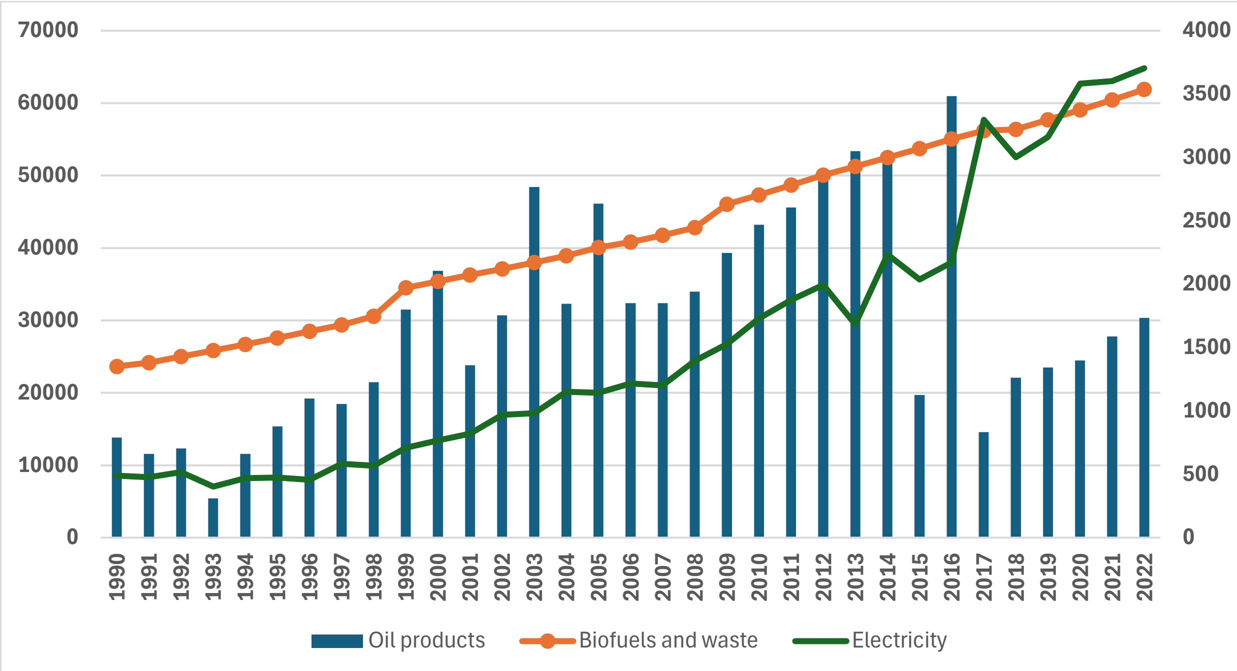

Figure 15: Residential total final consumption (TFC) by source in Togo
Data source: International Energy Agency, 2024

These fluctuations suggest that while oil products play a role in household energy consumption, their use has not been consistent, likely influenced by both external factors like global oil prices and internal factors such as income levels or policy changes promoting alternative energy sources. Biofuels and waste represent the dominant source of residential energy throughout the observed period. Starting at 23,646 units in 1990, biofuel usage has grown steadily over time, reflecting Togo's reliance on traditional biomass for residential energy needs, particularly in rural and lower-income households. This sustained increase, reaching 61,897 units by 2022, indicates that biofuels and waste remain critical for cooking, heating, and other domestic activities. The steady rise also reflects limited access to cleaner, modern energy sources in many areas. Biomass is often readily available and affordable but has environmental and health drawbacks, including deforestation and indoor air pollution. The trend suggests a continued reliance on traditional energy sources despite gradual modernization efforts, possibly due to socioeconomic factors and the high upfront costs of transitioning to alternative energy forms.

The use of electricity in the residential sector has shown a clear upward trend, albeit starting from a low base. Beginning at 489 units in 1990, electricity consumption rose gradually, with notable accelerations in recent years. For example, electricity uses nearly doubled from 1,875 units in 2011 to 3,704 units in 2022. This rise likely corresponds to improvements in electricity infrastructure, urbanization, and efforts to expand access to electricity across Togo. The increase in electricity usage suggests that more households are gaining access to the grid and that electrical appliances are becoming more common in Togolese homes. This growth could also indicate rising household incomes, allowing for greater adoption of electric lighting, cooking, and cooling solutions. However, despite the increase, the relatively low consumption level compared to biofuels implies that electricity access and affordability still pose challenges, especially in rural areas.

In summary, the residential TFC in Togo reflects a heavily biomass-dependent energy mix, with biofuels and waste consistently providing the largest share of household energy. Oil products are used to some extent but with notable volatility, possibly due to external price fluctuations and access issues. Electricity consumption, while growing, remains secondary but suggests a positive trend towards modern energy adoption. The continued dominance of biofuels highlights the need for policies promoting access to cleaner energy alternatives and improving electricity infrastructure, particularly in rural areas where reliance on biomass may contribute to environmental degradation and health issues. The gradual increase in electricity usage, however, is promising, indicating ongoing efforts to modernize the residential energy sector and improve energy access, which will be essential for sustainable development in Togo.

2.2.4. Renewable energy adoption and energy efficiency challenges in the household sector in Togo

2.2.4.1. Initiatives for renewable energy development and energy efficiency in the household sector in Togo

In Togo, several programs and projects have been implemented to promote renewable energy development and energy efficiency within the residential sector. The Togolese government, alongside international partners, has introduced initiatives to increase energy access, improve energy efficiency, and integrate renewable energy sources to mitigate energy poverty and support sustainable development. One of the prominent programs is the "CIZO" initiative, which aims to bring solar energy to rural households by providing affordable solar kits. Through a pay-as-you-go model, this initiative allows households in off-grid areas to access clean energy, reducing reliance on traditional biomass and kerosene. The project also includes financing options and partnerships with local providers to ensure that the solar kits are affordable and accessible to rural communities.

In addition to "CIZO," the Togolese government is involved in the African Development Bank's "Desert to Power" initiative. This program seeks to harness the solar potential of the Sahel region, including Togo, to expand renewable energy infrastructure. It promotes large-scale solar power deployment, contributing to residential energy availability through grid expansion and off-grid solutions. Another significant effort is the collaboration with the World Bank through the "Regional Off-Grid Electrification Project" (ROGEP). This initiative targets increased access to sustainable energy across West Africa by supporting off-grid solar power solutions. It encourages investment in the renewable energy sector, particularly in rural areas, by providing funding mechanisms and technical support to companies and households.

For energy efficiency, Togo has implemented awareness campaigns and incentives to promote energy-saving appliances and practices within households. The government encourages the use of energy-efficient lighting and promotes efficient cooking stoves to reduce household energy consumption, emissions, and deforestation. Through collaborations with development agencies, there are also training programs that aim to raise awareness of energy efficiency benefits, providing education on optimizing electricity use. Furthermore, Togo is part of the ECOWAS Renewable Energy Policy (EREP) and the ECOWAS Energy Efficiency Policy (EEEP). These regional policies set ambitious targets for renewable energy penetration and energy efficiency improvements, aligning with Togo's national strategies to increase renewable energy capacity and reduce overall energy consumption in the residential sector by 2030. Through these policies, Togo benefits from technical assistance and regional collaboration, which strengthen its renewable energy initiatives and energy efficiency measures.

Overall, Togo's efforts in the household sector focus on improving energy access, promoting renewable energy adoption, and enhancing energy efficiency to create a more sustainable and resilient energy system. These programs represent a comprehensive approach, combining technological, financial, and educational initiatives to foster a transition towards sustainable energy in Togolese households.

2.2.4.2.Challenges for renewable energy development and energy efficiency in the household sector in Togo

Renewable energy development and energy efficiency in the household sector in Togo face various interlinked challenges. These barriers are predominantly economic, infrastructural, regulatory, and social, limiting the widespread adoption of renewable energy technologies and energy-efficient practices essential for sustainable development and energy security.

The economic barriers to renewable energy and energy efficiency adoption in Togo's household sector are significant. The high upfront costs for renewable energy systems, including solar panels, inverters, and batteries, are often prohibitive for Togolese households, particularly in rural areas where incomes are generally lower than in urban regions. Research indicates that renewable energy installations in Sub-Saharan Africa are often costly due to the high import duties on renewable equipment and components, further straining household finances (Bawakyillenuo et al., 2018). The lack of accessible financing mechanisms exacerbates this issue; there are limited microfinance or low-interest loan options specifically designed to support renewable energy and energy efficiency investments. Without affordable financial products or incentives, low-income households are deterred from pursuing renewable energy solutions that could otherwise provide them with long-term savings (Energy Sector Management Assistance Program, 2020).

Infrastructural limitations play a crucial role in hindering renewable energy development and efficiency improvements. The grid infrastructure in Togo is underdeveloped, especially in rural and semi-urban areas, where grid connectivity is unreliable or altogether unavailable (World Bank, 2019). This limited grid connectivity prevents households from benefiting from on-grid renewable energy systems and impedes efficient electricity distribution from potential renewable sources. Additionally, energy storage infrastructure is underdeveloped. As many renewable energy sources, like solar power, are intermittent, a reliable storage solution is crucial for ensuring a consistent energy supply. However, in Togo, access to affordable energy storage solutions, such as batteries, is limited, causing renewable energy options to be unreliable for many households (IRENA, 2018).

The regulatory framework in Togo surrounding renewable energy is still evolving, resulting in a lack of clarity and stability in policy implementation. Currently, the regulatory environment lacks robust incentives for households to transition to renewable energy sources or adopt energy-efficient practices (AfDB, 2021). There are few, if any, subsidies, tax breaks, or incentives for households purchasing energy-efficient appliances or installing renewable energy systems. In contrast, other African nations with more developed renewable energy policies have demonstrated that incentives can significantly accelerate adoption rates. The absence of mandatory energy efficiency standards for household appliances further compounds this issue, as the market is often flooded with inefficient appliances that are cheaper upfront but have higher operational costs (Bimenyimana et al., 2021).

Additionally, the enforcement of any existing policies and standards remains inconsistent. Renewable energy adoption requires significant administrative support to oversee installation, ensure compliance, and incentivize efficient usage. However, inadequate regulatory oversight and enforcement limit the efficacy of these policies, making it challenging for Togo to scale up renewable energy in the household sector (African Development Bank, 2021).

Social factors also contribute to the low adoption rates of renewable energy and energy-efficient practices in Togolese households. Awareness of the benefits of renewable energy and energy-efficient appliances is relatively low, especially in rural areas where educational campaigns and demonstration projects are less accessible (Bawakyillenuo et al., 2018). Furthermore, many households rely on traditional biomass sources such as wood and charcoal for cooking and heating due to cultural preferences and the widespread belief that renewable energy solutions may be unreliable or insufficient to meet household needs. This perception is often reinforced by the lack of visible, large-scale renewable energy projects within the country, which could otherwise help establish renewable energy as a viable and reliable option (IEA, 2019).

Addressing these challenges will require a multi-faceted approach involving governmental support, private-sector engagement, and international collaboration. Key strategies include implementing subsidies and financing mechanisms specifically targeting renewable energy installations and energy-efficient appliances for low-income households. Strengthening the regulatory framework to provide clearer guidelines and more robust incentives can also encourage adoption. Moreover, infrastructure improvements, particularly in grid connectivity and energy storage, will be essential to support reliable renewable energy use in households. Public awareness campaigns and pilot projects can address social barriers by educating households on the long-term benefits of renewable energy and demonstrating its reliability. Through concerted efforts, Togo can improve its renewable energy adoption in the household sector, which will not only reduce the nation's dependency on imported fossil fuels but also promote sustainable development and enhance energy security for its citizens.

2.3. State of the art on renewable energy adoption interaction with energy efficiency investments

Sustainability concerns in the energy sector have been largely explored and even the literature underlined that energy efficiency (EE) and renewable energy (RE) adoption are two sides of the same coin in sustainable energy policy and green economy, it has seen separable advances (Sheffield, 1997). Indeed, the literature on the interaction between investment in EE and RE adoption only showed increases in separate studies on EE and RE.

Research highlights various theoretical frameworks and concepts that inform the study of energy efficiency (EE) and renewable energy (RE) adoption, illustrating how they have been used to understand household and organizational behaviors. A foundational theory mentioned is the Theory of Planned Behavior (TPB), which provides a psychological basis for understanding consumer decisions. According to Wall et al. (2021), TPB incorporates seven consumer characteristics (attitude, subjective norm, perceived behavioral control, perceived usefulness, curiosity, behavioral intention, and actual behavior) that influence choices related to goods and services, including renewable energy adoption. These factors emphasize the role of individual perceptions and beliefs, such as self-efficacy, environmental concern, and awareness of RE benefits, in shaping adoption behaviors.

The concept of risk aversion, as discussed by Hirst and Brown (1990), emerges as a critical barrier to different investments. Their findings reveal that uncertainty regarding energy savings, price fluctuations, and the irreversibility of investment decisions can deter consumers and organizations from committing energy-efficient technologies. This aligns with behavioral economic theories, which suggest that individuals often outweigh potential losses relative to gains, thus requiring targeted incentives to overcome these hesitations.

Economic theories also play a central role in the discussion of EE and RE adoption. For instance, Khalid et al. (2021) and Sardianou and Genoudi (2013) emphasize the importance of financial incentives, income, and education as determinants of adoption. These studies reflect broader principles of consumer choice theory, where relative advantages, ease of use, and economic returns shape the likelihood of investment. Additionally, the idea of externalities underpins policy recommendations such as carbon pricing, as highlighted by Radpour et al. (2021), who advocate for taxing fossil fuel power sources to internalize their environmental costs and incentivize RE adoption.

From a systems perspective, Lund (2007) and Ürge-Vorsatz et al. (2012) discuss the synergies between EE and RE within integrated energy systems. Their work aligns with systems theory, which suggests that interdependencies between components (such as EE reducing energy demand and enhancing the feasibility of RE technologies) can amplify overall system performance. This theoretical lens supports the idea that joint action on EE and RE adoption can achieve greater sustainability outcomes than separate efforts.

Moreover, decision-making theories are evident in Dato's (2017) application of a generalized ordered logit model, which reveals the interrelation between household decisions on EE investment and RE adoption. The model underscores how these choices are influenced by shared factors, such as sociodemographic, economic, and environmental variables, suggesting that they cannot be independently estimated. This is consistent with rational choice theory, which posits that individuals evaluate decisions based on expected utility, factoring in available information and constraints. Finally, the literature reflects elements of behavioral economics and sociology, as seen in studies by Tovar (2012) and Trotta (2018), which identify social context and conservation practices as predictors of energy-saving behaviors. These findings suggest that energy-related decisions are shaped not only by individual preferences but also by broader social norms and cultural attitudes.

Explicative factors and barriers to RE adoption were widely assessed to understand and improve the adoption process (Khalid et al. 2021; Wall et al. 2021; Atalay et al. 2016; Upton & Snyder, 2015; Viardot, 2013; Salim & Rafiq, 2012; Neij, 1997). Concerning barriers, previous studies illustrated by applying the extended theory of planned behavior (TPB) that the perception of self-effectiveness, environmental concern, renewable energy awareness, and beliefs about renewable energy benefits are important when stakeholders are running campaigns to promote consumer adoption of RE (Wall et al., 2021). Moreover, other studies conclude that implementing a carbon price on fossil fuel electric power sources and incentives for renewable energy can increase the share of renewable energies (Radpour et al., 2021). Environmental concerns, ease of use, financial incentives, and relative advantage were identified by Khalid et al. (2021) in the Poland context to accelerate RE adoption. In addition, Sardianou & Genoudi, (2013) identify income, education, and age to be positively correlated to the household's willingness to adopt RE.

The global energy demand increase is one of the challenges to climate change mitigation. Reducing this demand through investment in EE can provide important opportunities to reduce greenhouse gas emissions (OECD, 2015). Zhang et al. (2015) identified the determinants of EE investment and concluded that households' propensity to invest in energy-saving technologies depends mainly on home ownership, income, social context, and household energy conservation practices. For the firms, the better the energy management system is, the more likely the chances are for a positive decision on energy-efficiency investment (Cooremans & Schönenberger, 2019). However, Hirst & Brown, (1990) found that the tendency of consumers to be risk-averse reduces investments in EE due to uncertainty surrounding energy savings, energy price fluctuations, and the irreversibility of the investment. Sociodemographic, economic, and environmental variables are good predictors of both energy-saving behaviors and investment in energy-efficient appliances (Tovar, 2012; Trotta, 2018).

The separate literature on household behavior about RE adoption and EE investment converge in terms of the importance of key factors and raises a presumption of greater effectiveness of joint action (RE adoption and EE investment) compared to separate actions to energy sustainability (Abdmouleh et al., 2017; Dato, 2017; Ollier et al., 2020; Prindle et al., 2007). Indeed, despite the share of explicative factors (Sociodemographic, economic, and environmental) to RE adoption and investment in EE, most studies focus on either RE adoption or EE investment and explain the disparities between the effects of economic and environmental concerns. Interestingly if the two decisions are interrelated, they cannot be estimated independently (Dato, 2017). Since Sheffield's 1997 work, substantial advancements have been made in the literature regarding energy efficiency (EE) and renewable energy (RE). Initially, studies focused predominantly on either EE or RE in isolation. However, more recent research has begun to explore the interplay between the two, recognizing their combined potential in achieving sustainability goals. For example, Lund (2007) highlighted the synergies between EE and RE in integrated energy systems, showing that improvements in EE can enhance the effectiveness of RE technologies by reducing overall energy demand. Similarly, Ürge-Vorsatz et al. (2012) emphasized that simultaneous investments in EE and RE could lead to more significant reductions in greenhouse gas emissions compared to pursuing either strategy alone. Recent studies also suggest that policy frameworks should consider the co-benefits of EE and RE to maximize their impact on sustainable development (Popp et al., 2020). Overall, the literature has evolved to support a more holistic approach, advocating for integrated strategies that leverage the mutual benefits of EE and RE.

The potential synergies between these two issues can be a source of energy-sustainable programs inefficiency. While giving credit to existing literature that has shown theatrically and illustrated empirically the interaction between both households' decisions especially Dato (2017) using a generalized ordered logit model to illustrate this interaction, the current paper relies on fieldwork data to enhance potential interactions between the two decisions and underlines factors of households' energy-saving behavior. By integrating additionally several factors that can jointly affect adoption and efficiency investment such as residential, environmental, and other socio-demographics we contribute to the literature on improving renewable energy penetration and efficiency gains. Enhancing RE adoption impact and synergy on energy efficiency can accelerate energy sustainability. Assessing the impact of and the synergy between RE adoption and EE investment constitutes an opportunity to accelerate a path to preventing catastrophic climate change through the energy sector.

2.4. Materials and methods

2.4.1. Study area.

Renewable energy adoption and energy efficiency investment at the residential level are both affected by the current energy access rate, households' characteristics and environmental attitudes, different energy sources technologies availability, and accessibility (Khalid et al., 2021; Wall et al., 2021, Dato, 2017). Despite households' environmental attitudes being a subjective indicator, we used the regional distribution in terms of electricity access rate, solar home systems (SHS) market size, and its potential sensitivity to define the study area. To facilitate the data collection, social security, and the absence of terrorism in the area were added as the selection criterion.

In terms of energy access and energy transition, Togo's government identified the solar source as a foremost opportunity to reach SDG7 which aims to ensure access to reliable and modern energy services for all at affordable cost by 2030. However, households connected to an electrical grid (current electrification solution), and the market size repartition show different sources of inequalities (regional, residential). In terms of regional disparities, the Savanes region (11%) is the least lit according to the National Electrification Strategy (NES, 2018). However, this region was distinguished by a higher solar home systems (SHS) market size, a presence of social insecurity, and the movement of terrorist groups causing population displacement and difficult access. Indeed, in 2018 affordability analysis showed that at FCFA 160 per day, 31% of households can pay for off-grid solar products in this region.

Regarding electricity access, the Savanes region was followed by Plateaux (14%) and Centrale (18%). Although the two regions were safe in terms of social insecurity, Plateaux (2.9) was quoted at a higher rate of SHS market size (32%) at FCFA 160 per day report on electricity access while Centrale was quoted at (1.44). This indicates that households in the Centrale region were more unable to afford SHS compared to the Plateaux region. Furthermore, the sensitivity analysis showed that an increase in SHS price negatively impacts the Centrale region market size more than any other regional market. Indeed, the region's market can decrease from 26% to 8% of households that can pay for SHS at FCFA 160 per day and FCFA 280 per day respectively.

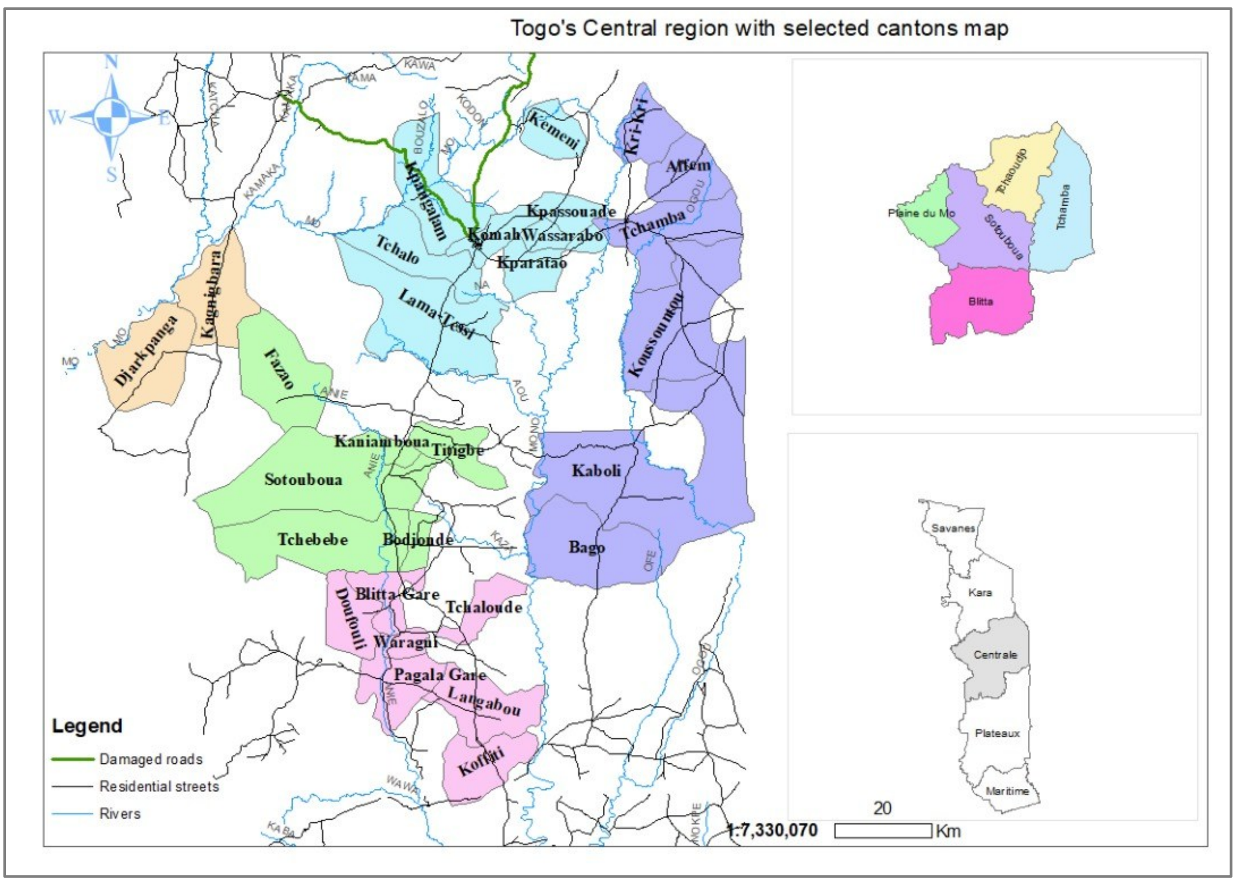

Figure 16: Map of the study area: Centrale region with selected cantons

Those challenges of clean energy access are the consequence and the cause of the current market being dominated by traditional energy sources at the national level. This research chose the Centrale administrative region of Togo (Mapped in **Figure 16**) which is divided into five districts, and sixty-one cantons as the study site to deeply understand the households' adoption of renewable energy, its synergy with and impact on households' investment in energy efficiency and their energy-saving behavior.

2.4.2. Sampling, and data collection methods

This analysis sample is designed to provide estimates for many indicators of environmental and energy characteristics of households in the Centrale region. It must be representative at the regional, prefectural, and residential levels. In total, the region contains 61 cantons which are divided as soon as possible into two zones (rural and urban). At the district level, each area except Mô (rural zone only) is divided into two residential (urban and rural) zones corresponding to nine zones. The sample selection was based on stratification using a two-stage random selection. This stratification was done to sort each district into canton areas and samples were selected independently in each district by a two-stage selection process. In the first stage, **30** cantons were selected randomly as the primary sampling unit to represent the district size. At the regional and district levels, the cantons (5) containing urban and rural areas were all selected after considering the representativity criterion. The units of this first selection were mapped below, and the size was the population settling in that area during the population and housing census conducted in 2022.

As long as the list of households to be served as the sampling frame is unknown, households were randomly selected in the second stage. In the second stage, a specific household number was selected in each canton. A total of n households was finally selected for the survey out of which n_1 households were interviewed in the entire region representing a response rate of $n_1/n * 100$ percent. To calculate n under unknown population size, we used Cochran's sample size formula: $n = [Z^2 * p(1-p)]/e^2$ with the margin of error $e = 5\%$, the confidence level Z is 1.96 for the two-tailed test and the default standard deviation p is fixed at 50%. Following Donald's, (1960); Hagburg's, (1968); Johnson's, (1959); and Miller & Smith's, (1983) recommendations for researchers to take a random sample of 10-20% of non-respondents to use in non-respondent follow-up analyses, we account for the likely non-response, 20% percent of n has been added. Therefore, the sample size is calculated and approximatively equals 462.

The data collection involved different module questionnaires which were used to collect a series of information about the households. The first module centered on the household's socioeconomics, including demographics, education, residential, and employment characteristics.

The second module covered household environmental attitudinal while the third was focused on household energy consumption. The last module focused on climate change information.

2.4.3. Theoretical model and empirical model

Household's energy consumption can be assimilated to other forms of consumer problems when it is separated from them (Ekholm et al. 2010). Using his budget (m) constraint, the household maximizes the discounted sum of utilities defined in (2.1) where ee, re, and c represent investments in energy efficiency and renewable energy and total other expenses, respectively; $k_1$and k_2 are the costs under which the two decisions are taken (Charlier et al., 2011; Dato, 2017; Ekholm et al., 2010; L. Zhang et al., 2015). m, d and β are respectively consumer-specific energy budgets, the share of the energy budget devoted to buying an amount of energy provided from non-clean sources of energy at each period t, and the discount factor.

$$\max_{d,re,ee} \sum_{t=0}^{p} \beta^t U(ee, re, d, c) \text{ ; program constraint: } m = d + k_1 ee + k_2 re + c \qquad (2.1)$$

Following Doni & Ricchiuti (2013), and Zhang et al. (2015), we consider that the consumer gets some disutility from consuming an inconvenient fuel. In addition, he gets some additional satisfaction by undertaking the two investments depending on his pro-environmental motivation since the two investments positively contribute to reducing global CO2 emissions. The first-order conditions of this maximization program give latent variables ee^* (energy efficiency investment) and re^* (renewable energy adoption) which are assumed to be determined by the vector of regressors X (economic and residential variables, variables of perception, commitment, and energy use).

$$re^* = X'\beta_1 + \epsilon_1 \text{ and } ee^* = X'\beta_2 + \epsilon_2 \qquad (2.2)$$

Where ϵ_1 and ϵ_2 are the error terms assumed to be jointly normally distributed with means 0 and variance 1. Moreover, to account for unobservable factors motivating jointly the two decisions we allow for some correlation ρ between the two errors. To deal with the non-zero correlation between the two decisions, Dato (2017) performed a generalized ordered logit model, and a bivariate probit model to assess the synergy between the two decisions. The potential synergy between RE adoption and EE investment draws its basis from the assumption that the household that only adopts RE or only reduces its energy consumption contributes more to the energy transition than the household that does nothing and less than the one who undertakes the two investments (Dato, 2017). However, the possible endogeneity of adopting renewable energy sources in a household's decision to invest in energy efficiency might generate a biased estimation. To overcome this issue, we apply an endogenous switching probit model to assess the impact of RE adoption on households' investment EE.

Despite the bivariate probit model providing the two decision factors and dealing with the correlation issue, the EE investment can be influenced by RE adoption suggesting the endogeneity issue. To handle the inconsistency estimation issue and draw jointly the divers to the two decisions we estimate the simultaneous equations model by employing an endogenous switching probit model with full information maximum likelihood (Di Marcantonio et al. 2022). Given households' decisions in RE adoption, the model splits the sample into two groups and expresses each of the EE investment functions (2.3).

Regime 1: $ee_{1i} = \alpha_1 Z_i + \varepsilon_{1i} \; if \; re_i = 1$ and Regime 2: $ee_{2i} = \alpha_2 Z_i + \varepsilon_{2i} \; if \; re_i = 0$ (2.3)

With re_i the decision to use or not renewable energy sources is assumed endogenous to the EE investment decision and can be estimated as re_i in (2.4), where household i's decides to adopt RE when the utility from adoption exceeds from non-adoption with X a vector of covariates that influence the decision to adopt. EE investments are divided into non-monetary and monetary categories. Non-monetary investment considers whether households factor in energy consumption when purchasing appliances (0: No, 1: Yes). Monetary investment tracks if households have installed energy efficiency items in the past decade (0: Have not installed, 1: Have installed). Explanatory variables include continuous variables such as household size, number of children under 18 and under 5, and the age of the household head. Categorical variables encompass district location (e.g., Tchaoudjo, Tchamba), marital status (e.g., single, monogamous), education level (e.g., no education, primary), and activity sector (e.g., agriculture, services). It also covers subjective life satisfaction (e.g., very pleased, not pleased), household house characteristics (e.g., flat, house), and duration of residence (e.g., less than 2 years, over 15 years). Binary variables include household head gender (male, female), residence type (urban, rural), homeownership status (owner, non-owner), and awareness of renewable energy, climate change, and government policies on green mobility and rural electrification (did know, did not know).

$$re_i^* = \alpha X_i + \eta_i \text{ such that } re_i = \begin{cases} 1 \; if \; re_h^* > 0 \\ 0 \; otherwise \end{cases} \quad (2.4)$$

The error terms η_i, ε_{1i} and ε_{2i} are assumed to have a trivariate normal distribution, with zero mean;

respective variance σ_η^2, σ_1^2 and σ_2^2 and covariance $Cov(\varepsilon_1, \varepsilon_2) = \sigma_{12}$, $Cov(\varepsilon_1, \eta) = \sigma_{1\eta}$ and $Cov(\varepsilon_2, \eta) = \sigma_{2\eta}$. Because of the correlation between η_i and ε_{1i}; $\eta_i$and ε_{2i} the expected value of ε_{1i} and ε_{2i} conditional on the sample selection is non-zero given as:

$$E[\varepsilon_{1i}|A_i = 1] = \sigma_{1\eta} \frac{\varphi(Z_i\alpha)}{\phi(Z_i\alpha)} = \sigma_{1\eta}\lambda_{1i} \text{ and } E[\varepsilon_{2i}|A_i = 0] = \sigma_{2\eta} \frac{\varphi(Z_i\alpha)}{\phi(Z_i\alpha)} = \sigma_{2\eta}\lambda_{2i} \quad (2.5)$$

where $\varphi(.)$ is the standard normal probability density function, and $\phi(.)$ the standard normal cumulative density function. The terms λ_{1i} and λ_{2i} refer to the inverse Mills ratio evaluated at $Z_i\alpha$ and are incorporated into outcome equations to account for sample selection bias. To compare the two groups of households, the expected probability to invest in EE regarding their RE adoption decision is expressed as (2.6) where $E[ee_{1i}|re_i = 1]$; $E[ee_{2i}|re_i = 0]$; $E[ee_{2i}|re_i = 1]$; and $E[ee_{1i}|re_i = 0]$ represent the expected probability for respectively RE users, non-users, users if they were non-users, and non-users if they were users.

$$\begin{cases} E[ee_{1i}|re_i = 1] = X_{1i}\beta_1 + \sigma_{1\eta}\lambda_{1i} \text{ and } E[ee_{2i}|re_i = 0] = X_{2i}\beta_2 + \sigma_{2\eta}\lambda_{2i} \\ E[ee_{2i}|re_i = 1] = X_{1i}\beta_2 + \sigma_{2\eta}\lambda_{1i} \text{ and } E[ee_{1i}|re_i = 0] = X_{2i}\beta_1 + \sigma_{1\eta}\lambda_{2i} \end{cases} \quad (2.6)$$

The treatment effects due to RE adoption decision (TT and TU) are given as (2.7)

$$TT = E[ee_{1i}|re_i = 1] - E[ee_{2i}|re_i = 1] \text{ and } TU = E[ee_{2i}|re_i = 0] - E[ee_{1i}|re_i = 0] \quad (2.7)$$

2.5. Results and discussion

2.5.1. Data cleaning and descriptive statistics

The database is cleaned regarding geographic location and household composition. Using GPS, errors in geographic information (district and residential area) are adjusted. In addition, outliers in household composition (age, number of children under 5 years old, activity sector) are also adjusted. We apply student's t and Pearson's chi-square tests to our quantitative and qualitative variables, respectively, to test if households significantly differ by renewable energy (RE) use. The results compiled in **Table 8** show that there are significant differences between RE users and non-users in their light turning off (energy-saving behavior) and energy efficiency (EE) items installation behaviors, suggesting that RE adoption plays a significant role in enhancing households' decision to invest in EE. For the total sample, 40% of households use RE and consider the energy consumption of appliances when purchasing, while only 12% of households take this concern into account and do not use RE. Furthermore, 16%, 14%, and 45% of households respectively occasionally, often, and always turn off lights when they leave the room and use RE, compared to their counterparts' non-user groups, where these statistics represent 8%, 4%, and 8% respectively. There are significant differences between RE users and non-users in terms of age, education, marital status of the household head, department, and residential area.

Departmental repartition shows that 31% of respondents are from the Tchaoudjo district and use RE, while RE users in Tchamba, Sotouboua, Blita, and Mô districts represent 16%, 15%, 13%, and 2% of the sample size, respectively **(**Table 8**)**. The geographic variable is important since the choice of energy source may depend on district endowment, characteristics, and cultural aspects. In addition, the residential repartition shows that 21.43% and 55.41% of the sample used RE and are living respectively in rural and urban areas. Most of the respondents have at least a basic level of education. Approximately 90% of respondents have attended at least a professional or alphabetization training. However, literacy is not negligible in the Centrale region regarding the percentage of households' heads without education (9%). Guta (2018) illustrated the importance of household welfare in investing in energy sustainability. Wealth is approximated in this paper by respondents' subjective life satisfaction and its repartition shows that 1.74% of respondents without distinguishing their RE adoption decision feel very satisfied, while 18%, 41.34%, and 16% of the sample used RE and feel respectively pleased, moderate pleased, and not pleased in their life.

Household environment attitudes were captured based on some environmental issues' importance in their localities. Households' subjective perceptions were scaled from not at all serious to extremely serious and the frequencies of each modality are illustrated in **Figure 17**. Most of the households interviewed perceived several environmental challenges to be serious or very serious threats to the country. For instance, 35.5%, 38.5%, 46%, 39.2%, 48.5%, and 43.5% respectively of respondents identified waste generation, air pollution, climate change, water pollution, lack of natural resources (forest, water, and energy) and endangered species and biodiversity issues as extremely important.

Table 8: Descriptive statistics comparing renewable energy users (RE) and non-users (non-RE)

Variables	Modalities	RES adoption: non-RE users	RES adoption: RE users	Difference or correlation tests
Investment in EE				
Non-monetary investment				
Considering the energy-consuming nature of appliances when purchasing	0: No	10.17	36.8	0.518
	1: Yes	12.99	40.04	
Monetary investment				
Installation of energy efficiency items over the past ten years	0: Have not installed	11.26	10.39	59.647***
	1: Have installed	11.90	66.45	
Explanatory variables				
Continuous variables (Student test)				
HH size		6.560	7.439	-0.879
Number of children <18 years old		3.149	3.062	0.087
Number of children <5 years old		1.065	0.938	0.127
HH head age		43.402	46.510	-3.108**
Categorial variables				
District (Localisation)	TCHAOUDJO	1.52	30.74	64.685***
	TCHAMBA	4.76	16.02	
	SOTOUBOUA	5.63	15.37	
	BLITTA	11.04	12.55	
	Mô	0.22	2.16	
Marital status of the HH head	Single	2.16	8.87	12.949***
	Monogamous	14.50	40.04	
	Polygamous	3.90	24.03	
	Widow/other	2.60	3.90	
Education level of the HH head	No education	0.65	8.44	11.790**
	Primary	5.84	15.15	
	Secondary 1st stage	5.63	24.03	
	Secondary 2nd stage	4.76	13.64	
	High school	2.38	7.58	
	Professional/Apha	3.90	8.01	
Activity sector of the HH head	Agriculture	12.77	33.12	6.007
	Services	3.46	18.18	
	Industry, electricity, water	1.95	6.06	
	Building/other	4.98	19.48	
Subjective life satisfaction	Very pleased	0.22	1.52	0.829
	Pleased	4.98	17.97	
	Moderate pleased	12.55	41.34	
	Not pleased	5.41	16.02	
HH house characteristic	Flat	0.65	1.95	
	House	16.45	60.82	
	Room	6.06	14.07	
Duration of residence (duration)	Less than 2 years	3.90	9.09	6.119
	2 to 5 years	5.63	13.85	
	6 to 15 years	4.55	13.85	
	Over 15 years	9.09	40.04	
Binary variables				
HH head gender	Male	19.91	69.91	2.253
	Female	3.25	6.93	
Residence	Urban	3.25	21.43	8.508***
	Rural	19.91	55.41	

Homeownership	Owner	16.67	59.74	1.526
	Non-owner	6.49	17.10	
Renewable energy awareness	Did not know	15.58	54.11	0.382
	Did know	7.58	22.73	
Climate change awareness	Did not know	17.75	61.04	0.386
	Did know	5.41	15.08	
Government green mobility policy awareness	Did not know	10.17	30.95	0.451
	Did know	12.99	45.89	
Government rural electrification policy awareness	Did not know	17.32	54.11	0.760
	Did know	5.84	22.73	

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Consumer attitudes and perceptions of goods and services choices lead to different equilibriums that can be suboptimal or optimal. To understand the perception of the Togolese in the Centrale region in opting for renewable energy sources, respondents in the study area were called to scale their extent in agreeing or disagreeing with different statements related to these products. The results compiled in **Table 9** indicate that more than half of the respondents agreed that they would pay more for RE (56.82%) if they had more money. The negative statements on RE were negatively scored on average. 29.55%; 34.4%; 25% and 43.18% of respondents disagreed respectively that there is already enough RE in the Togo energy supply, paying more will not increase the share of RE, there are no associated environmental benefits to RE, and there are not interested in RE.

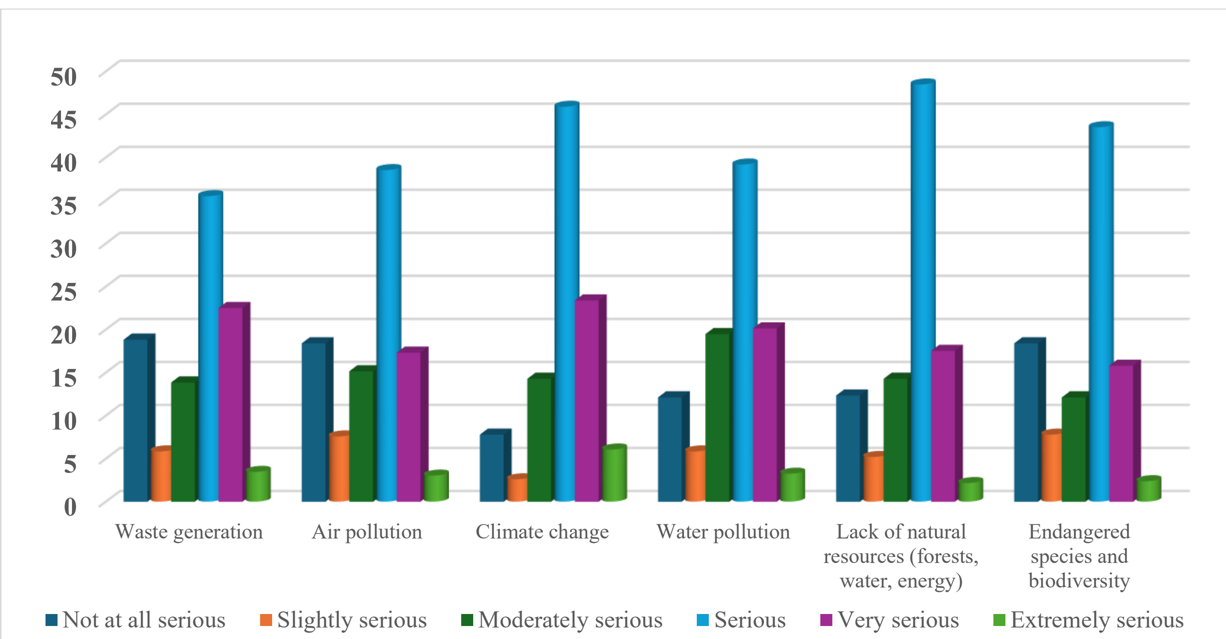

Figure 17: Household environment attitudes scaled from 1 "not at all serious" to 6 "extremely serious"

Generally, interviewees stated that they are willing to pay more for different sustainable products. This tendency is in favor of enhancing energy transition. Analyzing the knowledge level about the positive outcomes of these products, results show by the mean scale that respondents mostly disagreed that RE generally doesn't contribute to climate change mitigation indicating the positive attitude of consumers regarding their adoption. The state and local authorities should enhance providing the citizens with information on the environment in a bid to stimulate the desire to invest and participate in energy transition programs, as the active participation of citizens usually fosters the execution of targets which will, in turn, promote environmental sustainability.

Table 9: Consumer attitude and perceptions of renewable energy

To what extent do respondents agree or disagree with the following statements?	Percentage of consumer					**Mean score**
	Strongly disagree Score= -1	Disagree Score= -0.5	Neutral Score=0	Agree Score=0.5	Strongly agree Score=1	
Renewable energies (RE)						
If I had more money, I would pay more to use only RE.	9.09	20.45	13.64	56.82	0	0.091
I consider there are already enough RE in the supply	11.36	29.55	20.45	38.64	0	-0.068
I don't think that paying more will increase the share of RE	11.36	34.09	27.27	7.27	0	-0.148
I don't think that there are associated environmental benefits to RE	9.09	25	36.36	29.55	0	-0.068
I am not interested in RE	18.18	43.18	15.91	22.73	0	-0.284
I don't think I should pay more	6.82	18.18	31.82	43.18	0	0.057
I don't think I should pay more	8.66	35.71	11.26	42.86	1.52	-0.036

2.5.2. Non-monetary and monetary investments in energy efficiency and renewable energy adoption synergies: bivariate probit model

The potential synergy between RE adoption and EE investment draws its basis from the assumption that the household that only adopts RE or only reduces its energy consumption contributes more to the energy transition than the household that does nothing and less than the one who undertakes the two investments (Dato, 2017). In addition, it is impossible to sort household that only adopts RE ($re = 1$ and $ee = 0$) to one that only invests in EE ($re = 0$ and $ee = 1$) regarding their responsiveness to energy transition. Therefore, the ordered models can be a source of inconsistent estimation, making the bivariate model suitable to account for the correlation issue. Theoretically, by maximizing the expected utility, a risk-averse household i will decide to use the strategy (RE or EE) j, if the expected utility from using the specific strategy is greater than the one, he could have gotten without taking any measure. This utility U_{ij}^* following Thurstone (1927) represents the probability that household i adopts strategies j among the two (RE adoption and investing in EE).

$$\Pr(R_i = S_i|\delta, \xi) \equiv pr(S_i|\delta, \xi) = \Lambda_{ij} \dots \Lambda_{i1}\varphi_j(t|0, \xi)dt \tag{2.8}$$

With $\xi = \begin{bmatrix} 1 & \eta_{12} \\ \eta_{21} & 1 \end{bmatrix}$; $S_i = (S_{i1}, S_{i2})$ and Λ_{ij}an interval such that $\Lambda_{ij} = \begin{cases} (-\infty,\ X'_{ij} \text{ if } S_{ij} = 1) \\ [X'_{ij}\delta, \infty) \text{ if } S_{ij} = 0 \end{cases}$

and $\varphi_{ij}(t|0, \xi)$ a density function of a j adaptation strategy is assumed to be normally distributed. The bivariate probit model in the general form is given in (2.9) with X_{ij} the vector of exogenous predictors that could influence investments in clean energy and energy efficiency, δ are the regression coefficients, and τ_{ij} stands for the error term.

$$R_{ij} = X'_{ij}\delta_j + \tau_{ij} \tag{2.9}$$

The positive and significant correlation between RE adoption and monetary investment (M-EE) in EE is confirmed in the bivariate probit estimate. Indeed, the results of the bivariate probit estimation illustrated in **Table 10** show an athrho positive and statistically significant confirming the complementary relationship between the two decisions.

Being aware of RE, subjective life satisfaction, considering waste generation and natural resources depilation issues as a challenge faced by the country, and living in a house compared to in a flat positively and significantly increase households' likelihood to adopt RE. The positive effect of household life satisfaction was found in the Ethiopia context by Guta (2018). The author illustrated that wealthy households were more likely to adopt solar energy technologies compared to the poorer ones. In contrast, our results reveal that the higher the number of young persons is, the lower the household probability of investing in renewable energy. In addition, Blitta, Tchamba, Sotouboua, and Mô districts' households are less likely to adopt RE compared to Tchaoudjo. A similar result is observed for rural households compared to urban ones.

Furthermore, Table 10 indicates that environmental attitudes, household header age, and living sedentary seek in general to increase the household propensity to invest in EE. Trotta (2018) by using British household data, found a similar result concerning the importance of environmental attitudes in energy-saving behavior. Our results are consistent with Dato's (2017) findings which show that environmental motivations have a mixed effect on both investment in energy efficiency and adoption of renewable energy. People who consider environmental concerns as the greater country issues are more likely to invest in renewable energy. Investments in renewable energy are mostly undertaken to reduce CO2 emissions and probably less to save money. People for whom environmental issues are the priority and who are likely aware that renewable energy is a clean alternative and helps protect the environment will have more motivation to overcome barriers to adopting renewable energy.

Table 10: Non-monetary (NM-EE) and monetary (M-EE) investments in energy efficiency and renewable energy adoption synergies: bivariate probit model

	Bivariate model 1		**Bivariate model 2**	
	(1)	(2)	(4)	(5)
VARIABLES	re	NM-EE	re	M-EE
Household size	0.011	0.012	0.010	0.027
	(0.014)	(0.016)	(0.010)	(0.036)
Number of persons under 18 years old	-0.086***	0.015	-0.080***	-0.085**
	(0.003)	(0.023)	(0.006)	(0.038)
Number of persons under 5 years old	-0.051	0.061***	-0.052	0.226***
	(0.036)	(0.005)	(0.037)	(0.048)
Gender of household-headed (1= Male)	0.523	-0.728***	0.492	-0.040
	(0.437)	(0.143)	(0.441)	(0.056)
Age of household-headed	-0.001	0.003	-0.002	0.010***
	(0.002)	(0.004)	(0.003)	(0.001)
Marital status (Ref: Single)				
Married monogamous	0.125	-0.047	0.108	0.104
	(0.523)	(0.198)	(0.505)	(0.266)
Married polygamous	0.370	-0.285***	0.354	0.223
	(0.478)	(0.071)	(0.481)	(0.429)
Free union/other	0.030	-0.279***	0.025	-0.012
	(0.435)	(0.067)	(0.390)	(0.281)
Education level	-0.144***	-0.039***	-0.134***	-0.007
	(0.005)	(0.004)	(0.011)	(0.058)
Activity sector (Ref: Agriculture)				
Services	0.231	-0.122	0.283	0.061
	(0.183)	(0.079)	(0.173)	(0.116)
Industry, electricity, water	-0.136	-0.362**	-0.018	-0.274***
	(0.145)	(0.163)	(0.117)	(0.075)
Building, transport, trade	0.099**	-0.127	0.122***	-0.383***
	(0.047)	(0.151)	(0.030)	(0.113)
Subjective life satisfaction (0=not satisfied… 3=very satisfied)	0.164***	0.050	0.179***	-0.038***
	(0.037)	(0.087)	(0.031)	(0.014)
Department (Ref: TCHAOUDJO)				
TCHAMBA	-1.161***	0.059	-1.212***	-0.999***
	(0.073)	(0.209)	(0.020)	(0.317)
SOTOUBOUA	-1.149***	-0.396	-1.200***	-0.956***
	(0.044)	(0.281)	(0.069)	(0.259)
BLITTA	-1.833***	0.124	-1.851***	-0.979***

	(0.035)	(0.359)	(0.026)	(0.119)
MO	-0.398***	0.169	-0.570***	-0.472***
	(0.025)	(0.311)	(0.046)	(0.160)
Residence (1=Rural)	-0.545***	0.307***	-0.428***	-0.055***
	(0.121)	(0.026)	(0.141)	(0.015)
Homeownership (1=Owner)	-0.265	-0.226***	-0.269	-0.243***
	(0.614)	(0.079)	(0.515)	(0.009)
Home characteristic (Ref: Flat)				
House	0.538*	-0.565***	0.585*	0.119
	(0.298)	(0.081)	(0.341)	(0.202)
One room	0.048***	-0.613***	0.073***	0.025
	(0.009)	(0.209)	(0.009)	(0.055)
Number of years spent in the residential place	0.123***	0.072**	0.132**	0.131**
	(0.010)	(0.030)	(0.054)	(0.052)
Environmental attitudes				
Waste generation issue (1=not at all serious … 6=extremely serious)	0.091***	0.033***	0.078***	0.026***
	(0.014)	(0.010)	(0.019)	(0.004)
Air pollution issue (1=not at all serious … 6=extremely serious)	-0.111***	-0.131	-0.096***	0.016***
	(0.030)	(0.094)	(0.037)	(0.003)
Climate change issue (1=not at all serious … 6=extremely serious)	-0.121***	0.209***	-0.099***	-0.005
	(0.024)	(0.027)	(0.022)	(0.025)
Water pollution issue (1=not at all serious … 6=extremely serious)	0.026	0.060***	0.018	-0.060***
	(0.060)	(0.001)	(0.064)	(0.003)
Resources depilation issue (1=not at all serious … 6 = extremely serious)	0.088***	0.002	0.101***	-0.033*
	(0.019)	(0.019)	(0.013)	(0.019)
Biodiversity issue (1=not at all serious … 6=extremely serious)	-0.098***	-0.057	-0.097***	-0.062
	(0.026)	(0.074)	(0.019)	(0.065)
Climate change awareness (1= Aware)	-0.022	-0.109***	0.000	0.058
	(0.181)	(0.003)	(0.173)	(0.039)
Green mobility policy awareness (1= Aware)	0.010	-0.009	-0.047**	0.036
	(0.022)	(0.220)	(0.021)	(0.059)
Rural electrification policy awareness (1= Aware)	-0.240	0.319***	-0.203	0.236**
	(0.175)	(0.026)	(0.183)	(0.097)
Number of electronic appliances	0.092***	-0.055***	0.082***	-0.021
	(0.018)	(0.008)	(0.017)	(0.030)
Renewable energy awareness (1= Aware)	0.237*	0.325***	0.237*	0.183
	(0.127)	(0.054)	(0.142)	(0.112)
Constant	1.404***	0.216	1.202***	0.835***
	(0.138)	(0.446)	(0.095)	(0.059)
athrho		0.079		0.727***
		(0.052)		(0.097)
Observations	462	462	462	462

*** p<0.01, ** p<0.05, * p<0.1; Standard errors in parentheses

Note: renewable energy adoption decision (re); non-monetary energy efficiency investment (NM-EE); monetary energy efficiency investment (M-EE)

2.5.3. Renewable energy adoption impact on non-monetary and monetary investments in energy efficiency: Endogenous Switching Probit model (ESP)

Table 11 reports the full information maximum likelihood (FIML) estimates of the Endogeneous Switching Probit model for the households' decision to invest in EE. Columns 1 and 4 report the results for the selection equation that represents the factors influencing the decision of households to belong to RE adoptors or not. The outcome equation indicating the impact of the RE adoption decision on households' probability to invest in EE is provided in each sample by the column $re = 0$ for non-RE users and the column $re = 1$ for RE users. For both two models (non-monetary and monetary investments in EE), the correlation coefficients (ρ) between the residuals of the RE adoption decision and outcome are significantly different from zero according to the results of the likelihood ratio test $\rho 1 = \rho 2 = 0$.

Statistically, significant correlation coefficients suggest that the joint estimate based on the endogenous switching model was more efficient than separate regressions, implying that the two equations regarding the RE adoption decision are not independent and cannot be estimated separately. Furthermore, because of unobserved factors like environmental motivations, this statistic demonstrates a favorable interaction between the household's decision to invest in energy efficiency and adopt renewable energy. The sources of motives come from self-reporting questionnaires where respondents ranked the significance of various issues, including environmental ones. This could explain the positive connection by preventing the observation of the genuine environmental incentive and the accompanying cross-effect. In this way, a more environmentally conscious household is more likely to invest in renewable energy and energy efficiency. The estimation confirms the effects of RE awareness and environmental concerns. Indeed, being aware of RE, and considering waste generation and natural resources depilation issues as a challenge faced by the country, positively and significantly increases households' likelihood to adopt RE.

Subjective life satisfaction and living in a house compared to living in a flat positively and significantly increase households' likelihood of adopting RE. Considered as subjective indicators of household wealth, the costs of access to RE technologies require financial efforts borne by wealthier households and those living in their own homes compared with those in flats. Subjective life satisfaction is linked to adopting renewable energy for several reasons. Firstly, households that prioritize sustainability and environmental consciousness may derive a sense of fulfillment and satisfaction from reducing their carbon footprint using renewable energy. Additionally, financial investment in renewable energy technologies can provide households with a sense of control and autonomy over their energy consumption, leading to increased satisfaction with their living arrangements. Finally, the positive environmental impact of adopting RE may contribute to a greater overall sense of well-being and happiness (Guta, 2018).

Furthermore, Table 11 indicates that environmental attitudes, household header age, and living sedentary seek in general to increase the household propensity to invest in EE. Trotta (2018) by using British household data, found a similar result concerning the importance of environmental attitudes in energy-saving behavior. Our results are consistent with Dato's (2017) findings which show that environmental motivations have a mixed effect on both investment in energy efficiency and adoption of RE. People who consider environmental concerns as the greater country issues are more likely to invest in renewable energy. Investments in renewable energy are mostly undertaken to reduce CO_2 emissions and probably less to save money. People for whom environmental issues are the priority and who are likely aware that RE is a clean alternative and helps protect the environment will have more motivation to overcome barriers to adopting renewable energy.

In contrast, our results reveal that the higher the share of young persons is, the lower the household probability of investing in RE. One reason for the negative correlation between a higher proportion of young people and a lower household probability of investing in RE could be the difference in financial stability. Younger individuals may have limited financial resources and are more focused on meeting immediate needs, making it difficult for them to allocate funds toward long-term investments like RE. Additionally, younger individuals may have less awareness or understanding of the benefits and importance of renewable energy, leading to a lower likelihood of investment. This is consistent with the effect of household header age on EE investments and RE adoption.

The age of the respondent appears to be a relevant variable for the energy issues analyzed. Investments in RE adoption and EE investment depend positively on age. Earlier studies confirm that the probability of investing in RE and EE increases with age (Ameli & Brandt, 2015; Mills & Schleich, 2014), while it declines with age (Mahapatra & Gustavsson, 2008; Michelsen & Madlener, 2012). In addition, living in Blitta, Tchamba, Sotouboua, and Mô districts decreases households' propensity to adopt RE compared to Tchaoudjo. Known as the economic center in the Togo Centrale region, respondents in Tchaoudjo have fewer financial constraints than others in the rest of the region. A similar result is observed for rural households compared to urban ones. Rural households often have lower income levels, making the upfront costs of installing RE systems prohibitive. Finally, rural areas may have a stronger dependence on traditional energy sources, such as fossil fuels or biomass, due to limited infrastructure and availability of renewable energy options.

There is clear evidence supporting the idea that home characteristics may correlate with households' investments in RE and EE. The characteristics of dwellings seem to be relevant for technology adoption. Homeowners are more likely to invest in RE relative to flat renters with a substantially larger magnitude of the effect for relatively immobile investments. Nevertheless, renters do invest frequently in more energy-efficient appliances. These results confirm the analysis conducted by Ameli and Brandt. (2015). The ownership effect is also well-documented in the literature (Gillingham et al., 2012). The investment probability for RE depends positively on the time that households have already spent in their place. That could indicate in contrast with Ameli and Brandt' (2015) conclusion that households are more likely to invest in energy upgrades when they are not first moving into their home.

The expected investment in EE under the RE adoption decision estimates for the average treatment effects and heterogeneity effects are presented in **Table 12**. The expected probability to invest in EE for households that were using RE is about 0.401 for non-monetary investment and 0.668 for monetary investment, while it is respectively about 0.106 and 0.115 for the non-renewable energy user groups. This indicates that, on average, households that are using RE invest more in EE than their counterparts non-users. The treatment effects presented in the last column of Table 4 account for the selection bias arising from the fact that RE users and non-users may be systematically different (Abdulai and Huffman, 2014). Cells (c), and (c') represent respectively the expected probability to invest in non-monetary and monetary EE by the RE-users if they had decided not to use. Cells (d), and (d') represent respectively the expected probability to invest in non-monetary and monetary EE by the RE non-users if they had decided to use. The last row of Table 4 presents the heterogeneity effect. The significant heterogeneity effects imply that there are some important sources of heterogeneity that make households who have been already using RE more EE investors than households who have been not. The total impact of the RE adoption decision is identified in Table 4 by TH, and TH' indicates that in general RE adoption is an incentive action for households to non-monetary (0.295) and monetary (0.553) invest more in EE.

The adoption of renewable energy (RE) has demonstrated significant positive impacts on both monetary and non-monetary investments in energy efficiency, as evidenced by an expanding body of scholarly literature. Renewable energy technologies often serve as a catalyst for energy efficiency improvements by promoting a systemic transformation of energy consumption behaviors and infrastructure.

On the monetary side, the integration of renewable energy technologies tends to encourage increased investments in energy-efficient appliances and building retrofits. These investments are motivated not only by the desire to maximize the benefits of renewable generation but also by supportive policy mechanisms such as subsidies, feed-in tariffs, and tax incentives (IEA, 2021; Ameli & Brandt, 2015). For example, in residential and industrial settings, households and firms adopting solar PV systems often complement them with high-efficiency lighting, heating, ventilation, and air conditioning systems to optimize self-consumption and reduce reliance on grid electricity. As demonstrated by Zha et al. (2022), households investing in solar energy in China significantly increased their spending on energy-saving technologies, a trend attributed to their increased energy awareness and the financial savings enabled by renewable energy use.

Furthermore, renewable energy adoption can lower the marginal cost of energy, thereby creating financial space for additional efficiency-related investments. Empirical evidence suggests that regions with a high penetration of renewable energy observe increased energy efficiency investment rates, partially due to the economic spillover effects of the renewable energy sector, including job creation and local economic development (IRENA, 2020).

On the non-monetary front, the shift towards renewable energy fosters behavioral changes and raises awareness about sustainable energy consumption. Households and businesses that adopt renewable energy technologies often experience an increased sense of environmental responsibility, which contributes to energy-saving habits and the uptake of low-energy-use practices (Wolske et al., 2020). For instance, studies show that individuals using solar panels or small-scale wind turbines tend to become more energy-conscious, regularly monitoring and adjusting their consumption patterns to align with production cycles (Bollinger & Gillingham, 2012). This behavioral dimension is critical, as non-monetary investments, such as time spent learning about energy usage or adopting energy-saving habits, can significantly enhance overall energy efficiency without direct financial input.

Additionally, renewable energy deployment often stimulates innovation and knowledge transfer, leading to improvements in energy management systems, smart grids, and demand-side technologies (Kozluk & Zipperer, 2015). These advancements are essential in creating a more efficient energy ecosystem and are often facilitated through collaborative platforms, training programs, and community-based renewable energy projects.

Table 11: Endogenous switching probit (ESP) regression results for RE adoption impact on non-monetary EE (NM-EE) and monetary EE (M-EE) investments

	ESP for non-monetary investment in EE			ESP for monetary investment in EE		
	(1)	(2) (re=0)	(3) (re=1)	(4)	(5) (re=0)	(6) (re=1)
VARIABLES	RE	NM-EE	NM-EE	RE	M-EE	M-EE
Household size	0.010	0.008	-0.037***	0.007	0.014	-0.013*
	(0.017)	(0.024)	(0.009)	(0.016)	(0.042)	(0.008)
Number of persons under 18 years old	-0.089***	0.024**	0.095	-0.076***	0.007***	-0.224***
	(0.002)	(0.011)	(0.094)	(0.008)	(0.001)	(0.049)
Number of persons under 5 years old	-0.059	0.110**	-0.041	-0.078**	0.263***	0.520***
	(0.052)	(0.050)	(0.178)	(0.033)	(0.015)	(0.045)
Gender of household-headed (1= Male)	0.559	-0.705***	-1.864***	0.435	0.425	-0.811**
	(0.446)	(0.195)	(0.722)	(0.465)	(0.467)	(0.327)
Age of household-headed	0.001	0.005***	-0.001	0.003***	0.006	0.018***
	(0.003)	(0.002)	(0.006)	(0.000)	(0.010)	(0.004)
Marital status (Ref: Single)						
Married monogamous	0.146	-0.058	0.298	-0.077	0.315	-0.611**
	(0.462)	(0.382)	(0.474)	(0.457)	(0.237)	(0.260)
Married polygamous	0.458	-0.344***	-0.450	0.224	0.082	0.356
	(0.349)	(0.017)	(0.523)	(0.471)	(0.057)	(0.220)
Free union/other	0.017	-0.389***	-0.064	-0.212	0.697***	-0.677
	(0.317)	(0.093)	(0.719)	(0.516)	(0.057)	(0.545)
Education level	-0.162***	0.007	0.016	-0.117***	0.066	-0.134***
	(0.025)	(0.023)	(0.101)	(0.031)	(0.085)	(0.026)
Activity sector (Ref: Agriculture)						
Services	0.251***	-0.276***	-0.003	0.330**	-0.023	-0.022
	(0.036)	(0.027)	(0.128)	(0.149)	(0.116)	(0.140)
Industry, electricity, water	-0.110	-0.630***	1.159***	-0.059	-0.006	-1.249
	(0.204)	(0.178)	(0.193)	(0.173)	(0.068)	(0.813)
Building, transport, trade	-0.025	-0.268***	0.148	0.208*	-0.623***	-0.178
	(0.048)	(0.072)	(0.238)	(0.109)	(0.136)	(0.268)
Subjective life satisfaction (0=not satisfied… 3=very satisfied)	0.138***	-0.064*	0.244	0.121***	0.026	-0.177***
	(0.015)	(0.036)	(0.480)	(0.038)	(0.026)	(0.019)

Department (Ref: TCHAOUDJO)				-0.452***		
				(0.010)		
TCHAMBA	-1.260***	0.319***	0.918***		-0.815**	-0.490***
	(0.034)	(0.121)	(0.265)		(0.387)	(0.077)
SOTOUBOUA	-1.242***	-0.118	0.799		-0.797***	-0.813***
	(0.137)	(0.113)	(0.864)		(0.165)	(0.170)
BLITTA	-1.975***	0.678**	0.699		-0.781	-0.253*
	(0.078)	(0.276)	(0.735)		(0.822)	(0.152)
MO	-0.407**	0.387	-7.440***		-0.335	5.595***
	(0.172)	(0.285)	(0.120)		(0.385)	(1.006)
Residence (1=Rural)	-0.581***	0.448***	1.169***	-0.370	0.217	-0.619**
	(0.125)	(0.017)	(0.257)	(0.253)	(0.171)	(0.266)
Homeownership (1=Owner)	-0.269	-0.005	-1.078***	-0.240	-0.090	-0.329
	(0.413)	(0.172)	(0.120)	(0.533)	(0.201)	(0.379)
Home characteristic (Ref: Flat)						
House	0.867***	-0.456***	-0.504***	0.710*	0.136	-0.159***
	(0.206)	(0.066)	(0.173)	(0.369)	(0.147)	(0.004)
One room	0.500***	-0.286***	-1.023***	0.349***	0.033	-0.325***
	(0.045)	(0.007)	(0.235)	(0.042)	(0.183)	(0.100)
Number of years spent in the residential place	0.095***	-0.015	0.051	0.183***	0.140***	0.089
	(0.002)	(0.015)	(0.059)	(0.022)	(0.027)	(0.125)
Environmental attitudes						
Waste generation issue (1=not at all serious … 6=extremely serious)	0.098***	0.012***	-0.056***	0.026***	-0.052***	0.197***
	(0.001)	(0.001)	(0.007)	(0.009)	(0.010)	(0.062)
Air pollution issue (1=not at all serious … 6=extremely serious)	-0.127***	-0.065	-0.084**	-0.085***	0.066***	-0.020
	(0.039)	(0.102)	(0.040)	(0.030)	(0.005)	(0.027)
Climate change issue (1=not at all serious … 6=extremely serious)	-0.074***	0.178***	0.273***	-0.060***	0.050**	0.144*
	(0.004)	(0.002)	(0.071)	(0.021)	(0.022)	(0.084)
Water pollution issue (1=not at all serious … 6=extremely serious)	-0.003	0.049	-0.031	0.003	-0.051	-0.086***
	(0.049)	(0.074)	(0.313)	(0.055)	(0.065)	(0.029)
Resources depilation issue (1=not at all serious … 6 = extremely serious)	0.116***	-0.088***	0.309***	0.033***	-0.037***	-0.190***
	(0.032)	(0.018)	(0.046)	(0.011)	(0.013)	(0.028)
Biodiversity issue (1=not at all serious … 6=extremely serious)	-0.154***	-0.018	-0.308	-0.067***	0.002	-0.071

	(0.004)	(0.015)	(0.245)	(0.019)	(0.035)	(0.048)
Climate change awareness (1= Aware)	-0.001	-0.278***	0.363***	0.143	-0.241***	0.536
	(0.142)	(0.099)	(0.048)	(0.145)	(0.048)	(0.330)
Green mobility policy awareness (1= Aware)	-0.079***	0.054	-0.316**	-0.017	0.031	-0.325***
	(0.007)	(0.201)	(0.141)	(0.042)	(0.099)	(0.109)
Rural electrification policy awareness (1= Aware)	-0.332**	0.415***	0.308**	-0.136	0.399***	0.156**
	(0.160)	(0.144)	(0.142)	(0.183)	(0.121)	(0.061)
Number of electronic appliances	0.086***	-0.074***	0.011	0.087***	-0.069	0.059**
	(0.004)	(0.006)	(0.039)	(0.032)	(0.045)	(0.024)
Renewable energy awareness (1= Aware)	0.368***			0.206		
	(0.119)			(0.148)		
Constant	1.174***	0.861**	0.142	0.929***	0.411	2.800***
	(0.309)	(0.361)	(1.712)	(0.028)	(0.626)	(0.610)
σ_1			0.216			15.847***
			(0.183)			(2.949)
σ_2		-13.603***			-0.315	
		(1.489)			(1.652)	
LR test of indep. eqns.:	chi2(2) =	58.79; Prob > chi2 = 0.000		chi2(2) =	46.51; Prob > chi2 = 0.000	
Observations	462	462	462	437	437	437

*** p<0.01, ** p<0.05, * p<0.1; Standard errors in parentheses

Note: renewable energy adoption decision (re); non-monetary energy efficiency investment (NM-EE); monetary energy efficiency investment (M-EE)

Table 12: Conditional Expectations, Treatment, and Heterogeneity Effects

Samples	**Decision stage**				**Treatment effects**	
	To adopt		**Not to adopt**			
	NMEE	**MEE**	**NMEE**	**MEE**	**NMEE**	**MEE**
Households that adopted	(a) 0.401	(a') 0.668	(c) 0.132	(c') 0.114	TT =0.269*** (0.016)	TT' =0.553*** (0.017)
Households that did not adopt	(d) 0.362	(d') 0.103	(b) 0.106	(b') 0.115	TU =0.256*** (0.006)	TU' =-0.012 (0.008)
Heterogeneity effects	$BH1$ =0.039** (0.017)	$BH1'$ =0.565*** (0.013)	$BH2$ =0.026*** (0.010)	$BH2'$ =-0.001 (0.011)	TH =0.295*** (0.014)	TH' =0.553*** (0.015)

*** p<0.01, ** p<0.05, * p<0.1; Standard errors in parentheses

Note: Cells (a) and (b); (a') and (b') represent the expected outcomes observed in the sample for non-monetary and monetary investments

2.5.4. Households energy-efficiency behavior: Multinomial logit with relative risk ratios.

Household energy demand is not a direct demand for energy, but rather a derived demand to produce energy services (Trotta, 2018). Those services which are lighting, water heating, cooking, space heating, and air cooling derive energy demand that is embedded in a complex system involving technology adoption, behavioral economics, and psycho-social origin elements (Blasch et al., 2017; Fell, 2017). To enhance households' role in energy consumption and related emissions reduction, we employed a multinomial Logit with the relative risk ratio to analyze the factors of energy-saving behaviors adopted by households. The energy-saving behavior is captured in this context by the frequency with which households turn off the lights when they leave a room in their daily life. This curtailment action is used and recognized by households as the best to save energy in the home (Lundberg et al., 2019). Considering that households always turn off the lights when they leave a room is the base outcome, energy-saving behavior is modeled within the random utility modeling framework (Benedetti & Laureti, 2021; Hosmer et al., 2013). The utility of the certain alternative chosen by household i among the finite set (J) is W_{ij} and the associated random choice probability is noted $Prob(Y_i = j)$.

$$W_{ij} = \beta' x_{ij} + \vartheta_{ij} \text{ and } Prob(Y_i = j) = \frac{\exp(\beta' x_{ij})}{1 + \sum_{j=1}^{J} \exp(\beta' x_{ij})} \text{ for j} = 1,2,3,4 \tag{2.9}$$

From the point of view of the estimation, we used the odds ratio technique, and the relative risk ratio (rrr) obtained by exponentiating the multinomial logit coefficients, gives the proportionate change in the relative risk of choosing alternative j rather than the base alternative when x_i (explanatory variable) changes by one unit. The usefulness of this technique is the ratio does not depend on the other choices, which follows from the independence of disturbances in the original model (Benedetti & Laureti, 2021).

Table 13 compilates the results of the multinomial Logit estimation with a relative risk ratio where households never, often, occasionally, or always (base outcome) turn off the lights when they leave a room. Combining these results enhances different factors' effects on households' energy-saving behavior. Households are less likely energy savers when they are headed by males relative to females. The results show that households choose to always turn off the lights compared to never if they are in monogamous marital status relative to single, living in a house or room compared to flat, and being aware of climate change relative to not. In contrast, the relative risk of never turning off the lights relative to always would be expected to increase with the number of children under 18 and 5 years of age, life satisfaction, living in Blitta district compared to Tchaoudjo, living in rural areas compared to urban, and being aware to green mobility and rural electrification policies relative to not.

Table 13: Household energy-saving behavior: Multinomial logit with relative risk ratios (rrr)

VARIABLES	(1) Never	(2) Offen	(3) Occasionally
Household size	0.718**	0.901**	0.877
	(0.097)	(0.042)	(0.110)
Number of persons under 18 years old	1.467***	1.164**	1.189
	(0.074)	(0.082)	(0.146)
Number of persons under 5 years old	1.209**	1.269***	1.209
	(0.089)	(0.065)	(0.221)
Gender of household-headed (1= Male)	1.180	1.462***	1.542
	(0.516)	(0.134)	(1.074)
Age of household-headed	1.007	1.009	1.010
	(0.020)	(0.007)	(0.019)
Marital status (Ref: Single)			
Married monogamous	0.314***	0.611	0.597
	(0.109)	(0.338)	(0.312)
Married polygamous	0.572	0.335**	0.503*
	(0.339)	(0.169)	(0.189)
Free union/other	0.000***	7.649***	2.646
	(0.000)	(1.698)	(2.124)
Education level	1.209	0.877***	1.227
	(0.171)	(0.016)	(0.239)
Activity sector (Ref: Agriculture)			
Services	0.486	0.795**	1.101
	(0.306)	(0.072)	(0.348)
Industry, electricity, water	0.382	1.102	0.810
	(0.689)	(0.162)	(0.711)
Building, transport, trade	0.561***	1.067	0.992
	(0.102)	(0.118)	(0.235)
Subjective life satisfaction (0=not satisfied… 3=very satisfied)	1.990*	1.473***	1.133
	(0.788)	(0.005)	(0.324)
Department (Ref: TCHAOUDJO)			
TCHAMBA	0.000***	0.878	1.285
	(0.000)	(0.348)	(0.218)
SOTOUBOUA	0.461	0.524***	1.500
	(0.349)	(0.004)	(1.060)
BLITTA	1.766***	0.888***	2.905***
	(0.150)	(0.034)	(0.663)
MO	0.000***	0.000***	2.541***
	(0.000)	(0.000)	(0.304)
Residence (1=Rural)	2.737***	10.983***	0.881
	(0.521)	(2.749)	(0.262)
Homeownership (1=Owner)	0.838	0.876	0.986
	(0.191)	(0.380)	(0.948)
Home characteristic (Ref: Flat)			
House	0.365***	0.241***	0.265***
	(0.047)	(0.018)	(0.029)

One room	0.280***	0.479***	0.364***
	(0.124)	(0.034)	(0.041)
Number of years spent in the residential place	0.982	1.193***	1.202
	(0.089)	(0.056)	(0.248)
Environmental attitudes			
Waste generation issue (1=not at all serious … 6=extremely serious)	1.101***	1.251***	1.010
	(0.020)	(0.059)	(0.209)
Air pollution issue (1=not at all serious … 6=extremely serious)	0.738	1.008	0.954
	(0.178)	(0.069)	(0.243)
Climate change issue (1=not at all serious … 6=extremely serious)	0.822	0.824***	1.093
	(0.149)	(0.025)	(0.152)
Water pollution issue (1=not at all serious … 6=extremely serious)	1.063	0.850***	0.789
	(0.145)	(0.045)	(0.178)
Resources depilation issue (1=not at all serious … 6 = extremely serious)	0.966	1.341***	1.094
	(0.025)	(0.027)	(0.185)
Biodiversity issue (1=not at all serious … 6=extremely serious)	0.965	1.162***	0.970***
	(0.076)	(0.010)	(0.001)
Climate change awareness (1= Aware)	0.782***	0.752	1.188**
	(0.063)	(0.352)	(0.080)
Green mobility policy awareness (1= Aware)	1.218**	2.283***	1.306
	(0.104)	(0.418)	(0.684)
Rural electrification policy awareness (1= Aware)	1.421**	1.512*	0.752**
	(0.233)	(0.333)	(0.108)
Number of electronic appliances	1.033	0.984	1.011
	(0.027)	(0.026)	(0.021)
Constant	0.720	0.024***	0.284
	(1.034)	(0.003)	(0.295)
Observations	462	462	462

*** p<0.01, ** p<0.05, * p<0.1; Standard errors in parentheses.

Furthermore, energy-saving behavior analysis shows that the probability for households to always, occasionally, often, and never turn off the lights is respectively 52.4%, 18%, 24%, and 50.2% and depends on household characteristics, regional repartition, and environmental attitudes. These outcome probabilities plotted in **Figure 18** vary among residence areas, renewable energy adopters, and non-adopters. Especially, the probability for urban and renewable energy users to always turn off the lights is respectively 67%, and 55.2% relative to rural households (48%), and renewable energy non-users (43.2%). These results suggest that target policies are required to address specific barriers for different groups of energy consumers. For instance, promoting energy conservation actions and influence individual decision-making, providing households with feedback on their energy use and a better understanding of their energy practices can be helpful along with energy labels.

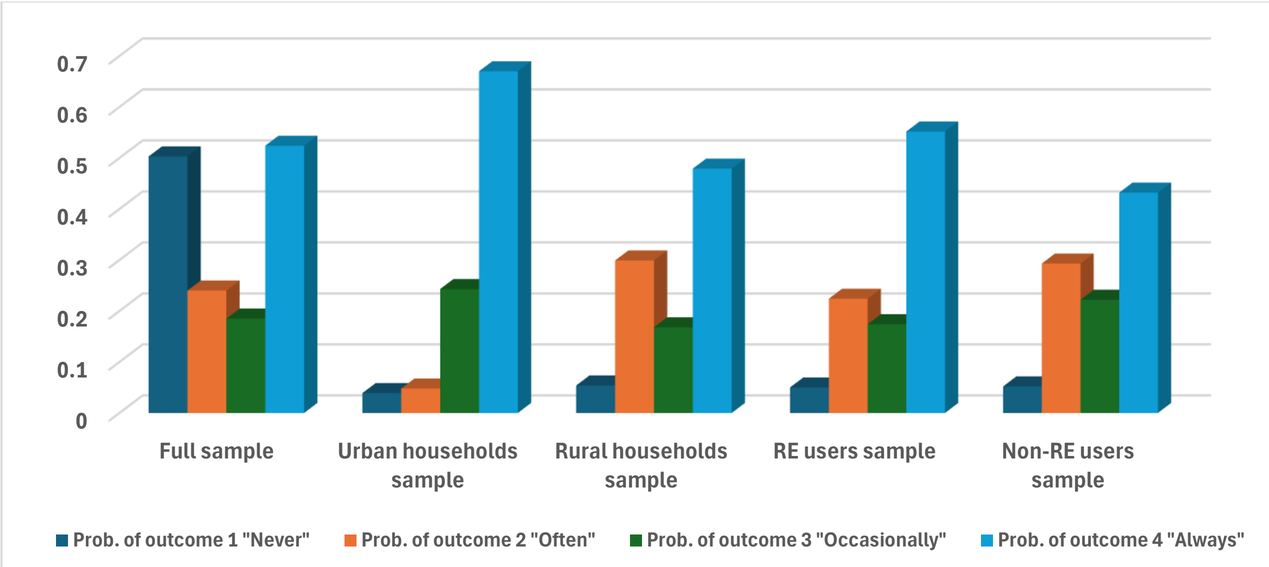

Figure 18: Outcome probabilities for households' energy-saving behavior

2.6. Conclusion and policy implications

By adopting renewable energy and investing in energy efficiency, households make an important contribution to reducing residential energy demand and CO2 emissions. Therefore, they are enhancing energy sustainability crucial for sustainable development goals (Fuso Nerini et al., 2017). Thus, understanding RE adoption and energy efficiency factors at the residential level is becoming increasingly predominant. This chapter aims to provide evidence regarding households' investment in EE, determinants, synergy, and impact of RE adoption. Primary data collected from 462 Togo Centrale region households provides a rich basis for such an investigation. Estimations using the Endogenous Switching probit model provide clear evidence supporting a synergistic relationship between the two households' energy sustainability channels. Both residential energy concerns are influenced by several factors such as household characteristics, departmental and residence repartition, and environmental attitudes. Moreover, adopting clean energy increases households' propensity to invest in energy efficiency. Indeed, the results indicate that renewable energy adoption incentivizes households to non-monetary (0.295) and monetary (0.553) invest more in energy efficiency.

The expected probability to invest in EE for households that were using RE is about 0.401 for non-monetary investment and 0.668 for monetary investment, while it is respectively about 0.106 and 0.115 for the non-renewable energy user groups. Fortunately, in the study area, many citizens stated they would pay more for RE. Analyzing the knowledge level about the associated environmental benefits of RE, results indicate that respondents mostly disagreed that these products do not generally contribute to climate change mitigation. In terms of barriers, finances, lack of recharging systems, and frequency of recharging limit respondents' willingness to choose RE. Subjective life satisfaction and living in a house compared to living in a flat positively and significantly increase households' likelihood of adopting RE. In addition, estimations indicate that household header age, sedentary lifestyles, and environmental attitudes all encourage households to invest in energy efficiency.

Concerning policy, one should first consider the two decisions of households' energy sustainability when designing incentive instruments for renewable energy adoption and energy efficiency investment. Policies that rely on factors that jointly affect the two decisions would benefit from the synergies that may exist between them. For example, promoting a net-zero-energy building by investing in both energy efficiency measures and renewable energy would facilitate reliance solely on renewable energy sources. Some strategies for promoting net-zero-energy buildings include implementing passive design techniques, such as optimizing building orientation and insulation, utilizing energy-efficient appliances and lighting systems, installing solar panels or wind turbines for renewable energy generation, and incorporating energy management systems to monitor and control energy usage. Offering incentives and subsidies to encourage adopting net-zero-energy building practices can also be an effective strategy. Energy demand would therefore be markedly reduced due to efficiency gains so that the remaining energy needs would be satisfied through renewable energy. Second, regulation of housing markets could help address split incentives by offering incentives to tenants to undertake investments in energy efficiency and renewable energy as well. Third, policies targeting investment in energy efficiency need to be improved.

The chapter has several limitations that should be acknowledged. First, it focuses exclusively on the Centrale region of Togo, which may limit the applicability of its findings to other regions or countries with differing socio-economic and cultural contexts. The sample size of 462 households, while significant, may not fully represent the diversity of household behaviors and constraints across the region. Additionally, the use of cross-sectional data restricts the analysis to a single point in time, making it difficult to capture long-term trends or dynamic changes in renewable energy (RE) and energy efficiency (EE) adoption. Subjective factors such as life satisfaction and environmental attitudes, though insightful, introduce potential biases due to their inherent variability. Finally, the reliance on an endogenous switching probit model simplifies household decision-making processes and may not fully capture the complexities of behavioral factors influencing RE and EE investments. Future research should aim to overcome these limitations by expanding the study's scope, incorporating longitudinal data, and factoring in external policy and market dynamics. This research on households' willingness to transit and to use efficient appliances powered by clean energy might provide incentive policies to promote sustainability in the energy importer country context.

Chapter 3: DYNAMIC ANALYSIS OF ENERGY POLICIES' IMPACTS IN TOGO: EVIDENCE-BASED ON COMPUTABLE GENERAL EQUILIBRIUM MODEL

Abstract

This chapter examines the macroeconomic impacts of energy policies in Togo, focusing on investments in research and development (R&D) and physical infrastructure for electricity and gas production. Using a dynamic computable general equilibrium model calibrated with Togo's 2018 Social Accounting Matrix, the analysis evaluates the individual and combined effects of these investments on GDP, savings, incomes total investment, and production in different economic sectors. Results indicate that R&D investments consistently yield higher economic returns, fostering innovation, reducing operational costs, and improving productivity. Physical investments, while more capital-intensive, enhance infrastructure reliability, promoting industrial growth and energy access. Combined strategies generate synergistic effects, amplifying GDP growth, government revenues, and household savings, with pronounced impacts in high-investment scenarios. However, disparities across sectors underline the need for targeted policies to address challenges in agriculture, informal production, and energy access. These findings highlight the critical role of integrated energy policies in driving sustainable economic development and resilience, offering valuable insights for Togo's energy transition and broader development agenda.

Keywords

Energy policy, investment, research & development, physical investment, CGE model

3.1. Introduction

Investments in research and development (R&D) and physical infrastructure for electricity and gas are pivotal for economic growth, structural transformation, and sustainable development. The dynamic macroeconomic impacts of these investments hinge on their ability to enhance productivity, stimulate innovation, and improve energy access, all of which are crucial for long-term economic resilience. Economic theory underscores the role of R&D in driving technological progress, which Solow (1956) identified as a central factor in long-term economic growth. Romer's (1990) endogenous growth model elaborates on this by showing how R&D investment can lead to increasing returns through knowledge spillovers. These spillovers enhance productivity across sectors, creating a virtuous cycle of growth. Jones and Williams (2000) quantify the social returns of R&D investments, which are significantly higher than private returns. This discrepancy suggests the need for public policies to subsidize R&D, particularly in energy sectors critical for sustainable development.

Similarly, physical investment in electricity and gas production and distribution has far-reaching macroeconomic implications. Calderón & Servén (2004) emphasize that infrastructure investment is a key driver of economic growth, particularly in developing countries, where inadequate energy infrastructure is a binding constraint. Energy infrastructure investments directly influence production costs, competitiveness, and overall economic output. For instance, Canning and Bennathan (2000) demonstrate a strong causal relationship between infrastructure investment and GDP growth in low- and middle-income countries. Their findings highlight the need for sustained capital allocation to energy sectors, where electricity and gas serve as backbone utilities for industrial and household consumption.

The dynamic effects of R&D and energy investments extend beyond immediate economic growth, influencing labor markets, income distribution, and environmental outcomes. Acemoglu et al. (2012) argue that targeted R&D investments in clean energy technologies can shift economies toward greener growth trajectories, reducing dependency on fossil fuels. This shift is significant given the global commitment to net-zero carbon emissions. Studies such as Popp (2019) show that R&D in renewable energy yields high returns by mitigating environmental externalities and fostering energy security. However, these returns are contingent on complementary investments in physical infrastructure for energy distribution, as Stern (2006) underscored in his energy and economic growth analysis.

Despite the evident benefits, scaling up investments in R&D and energy infrastructure involves significant challenges and trade-offs. Resource allocation decisions must consider opportunity costs, as argued by Barro (1990), who highlights the potential crowding-out effects of public investment on private capital formation. Similarly, Dabla-Norris et al. (2012) caution against the risks of debt accumulation when financing large-scale infrastructure projects. These concerns are particularly relevant in developing countries, where fiscal constraints and institutional weaknesses often undermine the effectiveness of public investment programs.

Togo faces critical challenges in achieving sustainable development. Its economy relies heavily on agriculture, accounting for about 40% of GDP and employing over 60% of the population (World Bank, 2022). Yet, structural issues, including low productivity, limited diversification, and vulnerability to climate change, undermine agricultural performance. Energy access and reliability further constrain growth and poverty alleviation efforts. As of 2020, only about 54% of Togo's population had access to electricity, with rural areas lagging at 36% (IEA, 2022). This disparity highlights the pressing need for electricity production and distribution infrastructure investment.

Energy issues are exacerbated by overreliance on imported fossil fuels, making the country vulnerable to global price fluctuations. The limited use of renewable energy resources, despite significant solar and hydropower potential, adds to this challenge. Simultaneously, the lack of robust research and development (R&D) systems hampers technological innovation and adaptation to local development needs. In Togo, R&D expenditure remains below 0.5% of GDP, far below the recommended 1-3% for developing countries (UNESCO, 2021). Energy access remains a critical barrier to development (Sarkodie & Adams, 2020). The country's installed capacity is 229 MW, with a national consumption of 1213 GWh in 2015. Togo faces an energy deficit, necessitating the import of 40% of its consumption from neighboring countries such as Ghana, Nigeria, and Côte d'Ivoire. Since 2014, Togo has set ambitious goals to increase its electrification rate to 50% by 2020 and 90% by 2030, as part of its strategy to achieve emerging country status. Togo emphasizes modern energy solutions to address economic, environmental, and social challenges simultaneously to meet these targets. Key questions for the energy sector include: What constitutes an optimal energy transition? How can it be made just? And what are the economic and social benefits of this process?

The interplay between these challenges forms a complex web of constraints on economic growth and human development. The energy sector's inefficiencies lead to high costs for businesses, deterring industrial expansion and job creation. This dynamic perpetuates dependence on low-value agricultural exports, limiting opportunities for structural transformation. Furthermore, climate change intensifies these issues by increasing weather variability, threatening agricultural yields, and straining already fragile energy systems. Togo's Vision 2030 agenda and National Development Plan (PND) recognize these challenges and prioritize investments in energy infrastructure and technological innovation. However, the implementation gap, coupled with limited financing and institutional capacity, remains a major hurdle. For example, while the government has set ambitious targets for renewable energy, progress has been slow due to inadequate private sector engagement and technical expertise.

The problem, therefore, lies in addressing Togo's dual deficit: inadequate energy infrastructure and low R&D investment. These deficits constrain productivity, limit economic diversification, and exacerbate social inequalities. Without targeted interventions, Togo risks falling short of its development goals, including the Sustainable Development Goals (SDGs), particularly those related to affordable and clean energy (SDG 7), decent work and economic growth (SDG 8), and climate action (SDG 13). Investments in research and development, alongside strategic physical investments in electricity and gas production and distribution, present a critical pathway for overcoming these challenges.

By fostering innovation, reducing energy costs, and enhancing access, such investments can catalyze inclusive economic growth and resilience in the face of climate and global economic shocks. Understanding the macroeconomic dynamics of these interventions is essential for designing effective policies and maximizing their impact. Therefore, the fundamental research question is: what are the dynamics of the economic impacts of different energy policies in Togo? Especially, this chapter focuses on how increasing investment in research and development, and physical investment for electricity and gas production and distribution dynamically impacts Togo’s economy, respectively. To this end, we rely on a dynamic computable general equilibrium model calibrated with Togo’s 2018 Social Accounting Matrix and simulate the macroeconomic impacts of this energy policy over ten years. The results reveal that R&D consistently generates the most substantial benefits across multiple dimensions (firms, households, and government savings) while physical investments provide the necessary infrastructure foundation. The combined investments amplify these impacts, highlighting the synergistic relationship between innovation and infrastructure

The remainder of this chapter is organized as follows: Section 2 describes economic and environmental statistics and energy policies in Togo; Section 3 reviews the literature on the dynamic impacts of the energy policies; Section 4 details the materials and methods used to achieve the chapter’s objectives; Section 5 presents and interprets the empirical results and their econometric analysis; and the conclusion follows in Section 6.

3.2. Economic and environmental statistics and energy transition policies in Togo

Togo, a West African nation, has been making strides in both economic development and environmental sustainability. With a population of approximately 8 million, Togo's economy has historically relied on agriculture, mining, and trade. However, the country faces challenges like poverty, unemployment, and environmental degradation. In recent years, significant efforts have been made to address these issues through policies aimed at economic growth, environmental protection, and energy transition. This section explores Togo's economic development, ecological pollution challenges, nationally determined contributions (NDCs), and energy transition policies to provide a comprehensive overview of the current state and prospects.

3.2.1. Togo's economic growth and environment pollution

Togo has experienced moderate economic growth over the past decade, steadily increasing its Gross Domestic Product (GDP) (**Figure** 19). The GDP growth rate averaged around 5% annually from 2010 to 2020, driven by agriculture, services, and construction sectors. Agriculture remains a vital component of Togo's economy, contributing approximately 40% to the GDP and employing around 60% of the labor force. Major agricultural products include coffee, cocoa, cotton, and various food crops. In recent years, Togo's economic policies have focused on diversification and industrialization to reduce reliance on agriculture and increase value-added activities. The mining sector, particularly phosphate mining, has also been a significant contributor to GDP, with Togo being one of the largest phosphate producers in Africa. Additionally, the government has invested in infrastructure development, such as road construction, port expansion, and energy projects, to stimulate economic activities and attract foreign investment.

From 2000 to 2021, Togo's economic and environmental trends reveal significant insights through GDP per capita and CO2 emissions per GDP unit. GDP per capita, measured in constant 2015 US dollars, increased from $497.06 in 2000 to $631.65 in 2021. Despite periods of stagnation and decline, such as from 2004 to 2006 and 2007 to 2009, the economy generally showed a positive trajectory. Notably, from 2013 onward, there was consistent growth, suggesting favorable economic conditions or effective policies. In terms of CO2 emissions, fluctuations were evident, with a high of 0.7107 kg per dollar of GDP in 2009. This peak may have been driven by increased industrial activities or reliance on carbon-intensive energy sources. However, a gradual decline followed, with emissions dropping to 0.3012 kg by 2021. The downward trend in emissions intensity indicates potential improvements in energy efficiency or a transition to less carbon-intensive economic practices. The period between 2000 and 2010 was marked by slow economic growth and high emissions intensity, hinting at an economy heavily reliant on fossil fuels. From 2010 onward, as GDP per capita grew, emissions per GDP unit fell, reflecting a decoupling of economic growth from emissions and signaling a shift toward sustainability. This suggests that economic growth has become more environmentally friendly, possibly due to policies promoting green energy and efficiency. The early 2000s indicate economic instability, while post-2010 improvements hint at stabilization efforts. The global financial crisis of 2008 likely contributed to economic slowdowns, with recovery phases marked by stronger growth. Overall, these statistics highlight the importance of energy and climate policies in reducing emissions while sustaining economic progress. The decline in CO2 intensity underscores positive changes, and the consistent GDP growth points to economic diversification. Continued investment in sustainable practices and green technology will be crucial for long-term stability and resilience.

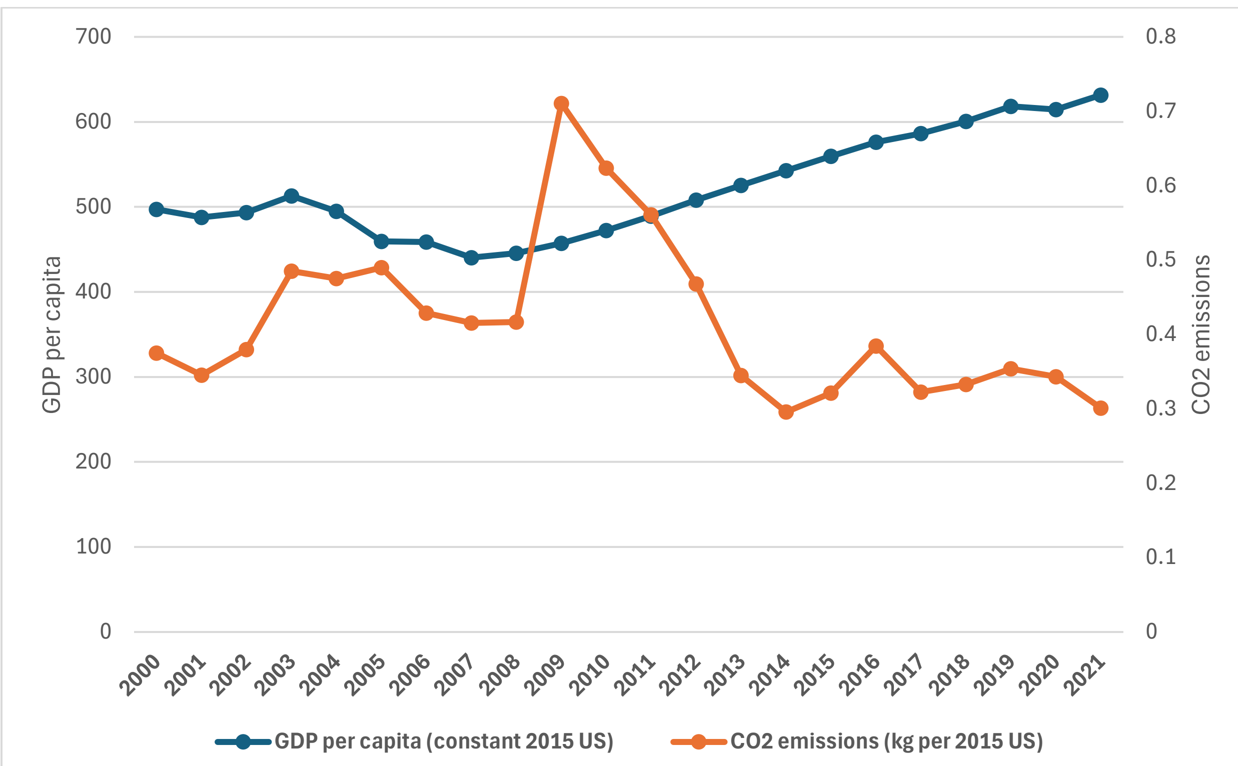

Figure 19: Togo's economic growth and environment pollution
Data source: World Bank, 2024

3.2.2. Public investments in multiple renewables

Figure 20 showing Togo's public investments in multiple renewables from 2013 to 2021 reveals fluctuating commitment levels, measured in millions of 2020 USD. In 2013, investment was minimal at $0.15 million, but there was a significant increase to $9.48 million in 2014, possibly due to a policy shift or specific funding initiative. This was followed by a decline to $4.96 million in 2015, showing a reduction but still representing a notable investment compared to the initial low levels. However, there was no recorded investment in 2016 and 2017, suggesting a potential shift in priorities, funding reallocations, or a lack of renewable energy projects during that period, which may have impacted the momentum for renewable energy development. Investments resumed in 2018 with $0.67 million, followed by gradual increases in 2019 and 2020, indicating a renewed, though modest, interest in renewable energy development, possibly aligned with global climate goals or national energy strategies. A significant surge occurred in 2021 with $9.31 million invested, nearly matching the 2014 high and suggesting a stronger commitment to renewable energy, likely influenced by climate action policies, international support, or increased energy demand. This trend highlights a renewed focus on renewables, but a more consistent investment pattern could be necessary for a substantial and sustained impact on Togo's energy sector.

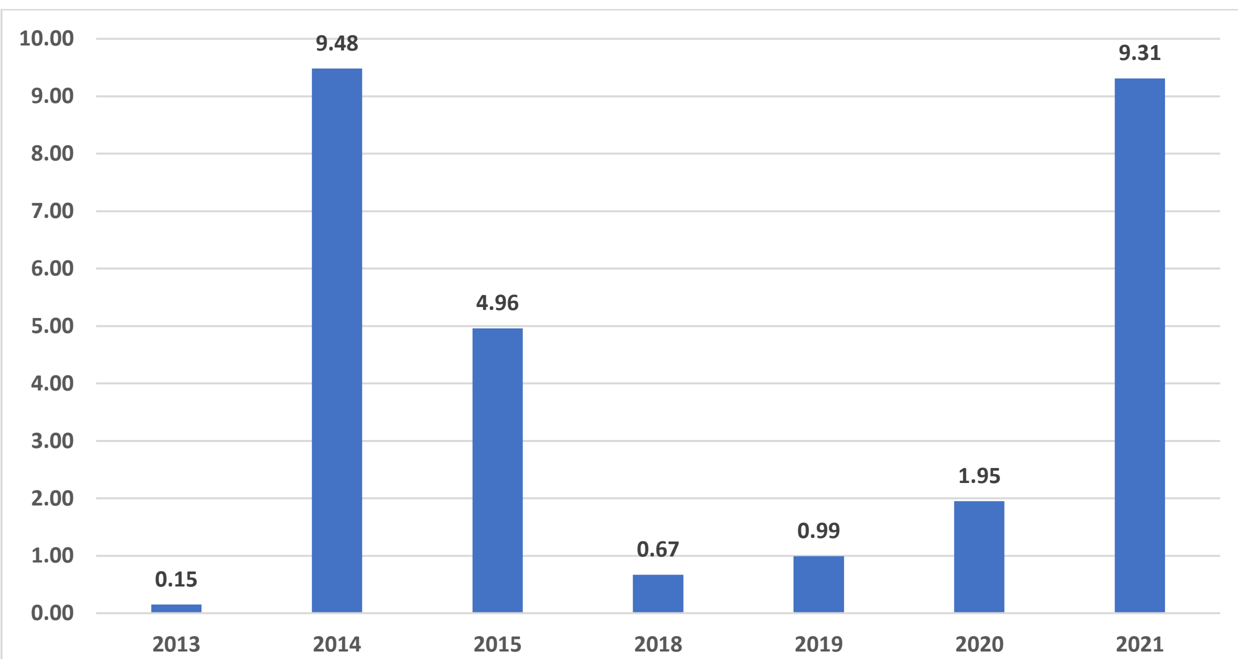

Figure 20: Public investments in multiple renewables (2020 million USD)
Data source: Our World in Data, 2024

In Togo, the challenge of ensuring sustainable and reliable access to electricity and gas for both urban and rural populations highlight significant issues related to physical investment. Togo's energy sector relies heavily on physical infrastructure for production, transmission, and distribution, and much of this infrastructure is outdated and inadequate to meet growing demand. The dependence on limited hydroelectric and thermal power plants, coupled with an underdeveloped gas supply chain, exacerbates the country's energy insecurity and stifles its economic development. One of the primary problems in Togo’s energy sector is insufficient investment in modernizing and expanding physical infrastructure. Existing electricity transmission lines, for instance, suffer from frequent outages due to both age and limited maintenance. This results in unreliable electricity access, which deters investment in other sectors and hampers industrial productivity (Kouton & Aboh, 2020). Additionally, Togo's gas infrastructure is limited, with little investment in pipelines or distribution networks. The lack of a cohesive gas supply chain means that even though liquefied petroleum gas (LPG) could serve as a cleaner alternative to biomass for cooking, access remains limited to urban centers and is priced beyond the reach of many households (USAID, 2020).

Financial constraints play a central role in the shortage of physical investment. Togo’s reliance on foreign aid and loans for energy sector improvements limits the scope of projects, and securing sustainable financing has been a consistent challenge (AfDB, 2018). Private sector participation remains limited due to concerns about the regulatory environment, political stability, and return on investment. Despite the introduction of new policies encouraging private sector involvement, high initial costs and low potential for immediate returns discourage investment in large-scale infrastructure projects (IMF, 2022). Moreover, the need for renewable energy investment has become increasingly pressing due to environmental concerns and the volatility of fossil fuel prices. Togo’s geographic potential for solar and wind energy is largely untapped, and the required physical infrastructure, including solar farms and wind turbines, has not been fully explored or supported by adequate policy frameworks (Energy Commission of Togo, 2023). Without significant investment in these areas, Togo will likely continue to rely on imported fossil fuels, which are both costly and environmentally damaging.

Overall, the issue of physical investment in Togo’s electricity and gas sectors poses a complex challenge, impacting economic growth, household welfare, and environmental sustainability. To overcome these barriers, increased financial resources, stronger private-sector partnerships, and clear policy support for renewable energy are essential.

3.2.3. National determined contributions and energy transition

Togo's commitment to addressing climate change and promoting sustainable development is reflected in its Nationally Determined Contributions (NDCs) under the Paris Agreement. The NDCs outline the country's targets and actions to reduce greenhouse gas (GHG) emissions, enhance climate resilience, and transition to a low-carbon economy. Key sectors targeted in Togo's NDCs include energy, agriculture, forestry, waste management, and transport.

The energy sector is central to Togo's efforts to achieve its climate goals, with a focus on increasing the share of renewable energy in the national energy mix. Togo has abundant renewable energy resources, including solar, wind, and hydropower, which offer significant potential for sustainable energy development. The government has set ambitious targets to increase the installed capacity of renewable energy, aiming to achieve 50% of electricity generation from renewable sources by 2030. Solar energy is a key component of Togo's energy transition strategy. The country receives high levels of solar radiation, making it well-suited for solar power generation. Several large-scale solar projects have been initiated, including the construction of solar farms and the promotion of decentralized solar systems for rural electrification. The Scaling Solar initiative, supported by the World Bank, aims to develop up to 90 MW of solar capacity, providing clean and affordable energy to millions of people.

Wind energy also holds potential in Togo, particularly in coastal areas where wind speeds are favorable for power generation. Feasibility studies and pilot projects are underway to assess the viability of wind energy and attract investments in this sector. Hydropower, although limited in potential compared to solar and wind, remains an important part of the renewable energy portfolio, with existing and planned projects contributing to the overall energy mix.

In addition to renewable energy development, energy efficiency measures are being promoted to reduce energy consumption and GHG emissions. The government has introduced energy efficiency standards and labeling for appliances, as well as initiatives to improve energy efficiency in buildings and industrial processes. Public awareness campaigns and capacity-building programs aim to encourage energy-saving practices among consumers and businesses.

Togo's NDCs also emphasize the importance of sustainable land management and reforestation to enhance carbon sequestration and reduce emissions from deforestation and land degradation. The country has launched reforestation programs, including the planting of millions of trees and the restoration of degraded lands, to increase forest cover and improve ecosystem resilience. Agroforestry practices are being promoted to integrate tree planting with agricultural activities, providing multiple benefits such as improved soil fertility, increased crop yields, and carbon sequestration.

The transport sector is another focus area for emission reduction efforts. Togo aims to modernize its transport infrastructure and promote the use of cleaner and more efficient vehicles. The development of public transport systems, the promotion of non-motorized transport, and the introduction of fuel efficiency standards for vehicles are key strategies to reduce emissions from the transport sector. Additionally, initiatives to improve road infrastructure and reduce traffic congestion are being implemented to enhance mobility and reduce fuel consumption.

Waste management is also addressed in Togo's NDCs, with a focus on reducing methane emissions from landfills and promoting waste-to-energy solutions. The development of sanitary landfills, the promotion of recycling and composting, and the capture and utilization of landfill gas are among the measures being implemented to improve waste management practices and reduce emissions.

In summary, Togo's Nationally Determined Contributions and energy transition policies reflect a strong commitment to addressing climate change and promoting sustainable development. The focus on renewable energy, energy efficiency, sustainable land management, and cleaner transport systems aims to reduce GHG emissions and enhance climate resilience. Continued efforts to implement and scale up these initiatives and support from international partners will be crucial for achieving Togo's climate goals and ensuring a sustainable future.

3.2.4. Overview of energy policies in Togo

In recent years, Togo has experienced a remarkable surge in investments across its electricity and gas production and distribution sectors, with both physical infrastructure and research and development (R&D) receiving significant attention. Physical investments have centered on upgrading and modernizing infrastructure to meet rising energy demands. Between 2020 and 2024, the country allocated approximately USD 500 million to enhance its thermal power plants, resulting in a 25% increase in installed capacity. A standout project is the Blitta Solar Farm, a 50

MW renewable energy initiative completed in 2023, which highlights Togo's drive to diversify its energy portfolio with sustainable sources. Substantial investments in gas infrastructure have also been made, with over USD 200 million directed towards expanding pipeline networks and storage facilities. These improvements aim to bolster the reliability and efficiency of natural gas distribution nationwide.

R&D investments, while comparatively smaller, have shown a promising upward trend. From 2020 to 2024, the Togolese government, in partnership with organizations like the African Development Bank (AfDB) and the International Renewable Energy Agency (IRENA), allocated USD 50 million to innovative energy projects. These initiatives focus on advancing solar and wind energy technologies, improving energy storage, and incorporating smart technologies into the national grid. For example, a notable 2022 project explores the development of advanced photovoltaic materials optimized for Togo's climate, aiming to boost solar panel efficiency by 15%. The growth in investments has been bolstered by public-private partnerships (PPPs), which have successfully mobilized domestic and international capital. In 2023 alone, PPPs contributed to approximately 40% of the total energy sector investments. Collaborative efforts, particularly those involving the Togolese Electricity Company (CEET) and international firms, have facilitated technology transfers and capacity-building initiatives.

Togo's supportive policy and regulatory framework have played a key role in attracting and sustaining energy sector investments. The government has implemented a range of incentives, including tax reductions for energy projects and import duty exemptions on renewable energy equipment. Additionally, dedicated grants and R&D subsidies have encouraged innovation and technological advancements.

The Ministry of Energy leads efforts to ensure a stable investment climate, implementing reforms that have streamlined permit and licensing processes. Since 2021, bureaucratic delays have decreased by 30%, making it easier for local and international investors to initiate and operate projects. Regulatory measures also promote private-sector participation by ensuring fair access to the grid and transparent pricing mechanisms. Electricity tariffs are carefully regulated to strike a balance between consumer affordability and producer profitability, fostering sustainable returns on investments. To further support R&D, Togo has embedded innovation within its national energy strategy. The creation of an Energy Innovation Fund, with an annual budget of USD 20 million, underscores the government's commitment to research. Policies encourage partnerships between academic institutions and the private sector, enabling knowledge exchange and the commercialization of cutting-edge technologies.

Environmental regulations have also been strengthened to align with global sustainability standards. The National Environmental Agency enforces these measures, ensuring that energy projects adopt cleaner technologies and contribute to Togo's climate goals. Through strategic investments, a strong policy framework, and robust public-private partnerships, Togo is advancing its energy sector with a clear focus on sustainability and innovation. With continued emphasis on infrastructure development, technological progress, and investor-friendly policies, the nation is well-positioned to achieve energy security and drive long-term economic growth.

3.3. Literature review on economic impacts of energy policies

3.3.1. Theoretical foundations on the dynamics of the energy policies analysis

The dynamics of the energy-economic-environmental impacts of different energy policies are intricate and multifaceted, involving a complex interplay between technological advancements, economic development, and environmental sustainability (Connolly et al., 2016; Gökgöz & Güvercin, 2018; Tufail et al., 2019; Haque, 2022; Prina et al., 2020; Vidal-Amaro et al., 2015). Economic and environmental theories provide a diverse and comprehensive foundation for understanding the intricate dynamics between natural resources, economic activities, and ecological systems. Classical economists, such as Adam Smith, underscored the importance of natural resources in production but often regarded them as abundant and freely available, leading to limited consideration of environmental constraints. In contrast, neoclassical economics introduced the concepts of externalities and market failures, recognizing that economic activities can lead to environmental degradation (Pigou, 1920). To address these externalities, interventions such as taxes and regulations are necessary, as posited by Pigou in 1920.

Building on these foundations, ecological economics, championed by scholars like Herman Daly, integrates ecological principles into economic analysis (Daly, 1991). This field emphasizes the limits to growth and advocates for a steady-state economy that maintains environmental balance, highlighting the necessity of sustainable practices to ensure long-term ecological stability. The concept of sustainability itself is central to many environmental theories, positing that development should meet the needs of the present without compromising the ability of future generations to meet their own needs. The Environmental Kuznets Curve (EKC) hypothesis provides another perspective, suggesting that environmental degradation initially increases with economic growth but eventually declines as societies reach a certain level of income and can afford cleaner technologies and stricter regulations (Grossman & Krueger, 1991). The authors introduced this concept in 1991, indicating that economic development could lead to environmental improvements. Complementing this, the ecological footprint concept measures the demand placed on Earth's ecosystems by human activities, highlighting the sustainability challenges posed by overconsumption and overpopulation. This concept, developed by Wackernagel and Rees in 1996, underscores the critical need for sustainable resource management (Wackernagel & Rees, 1996).

Energy theories also play a crucial role in understanding the interplay between economic activities and environmental health (Hubbert, 1956; Hall et al., 2009). Energy Return on Investment (EROI), for instance, measures the amount of usable energy obtained from a particular energy resource relative to the amount of energy expended to obtain that energy. A higher EROI indicates more efficient energy production, as detailed by Hall et al., (2009). Another significant energy theory is the Peak Oil Theory, proposed by Hubbert in 1956. This theory predicts the point at which global oil production will reach its maximum rate, after which production will decline, underscoring the finite nature of fossil fuel resources and the impending need for alternative energy solutions. Integrated theories emphasize the interconnectedness of energy systems, environmental health, and economic activities, arguing that changes in one domain inevitably affect the others (Forrester, 1961; Stern, 2004). These theories advocate for a holistic approach to policy and planning, as highlighted by Stern in 2004. System dynamics, a methodology introduced by Forrester in 1961, uses feedback loops and time delays to simulate the interactions between energy, environment, and economy. These models aid in understanding the complex behaviors and potential tipping points within these systems, providing valuable insights for decision-making and long-term planning.

The rich theoretical literature on energy-environment-economy dynamics offers diverse perspectives that are crucial for informing empirical research and policymaking. From classical economic theories to modern ecological economics, and sustainability concepts to energy theories like EROI and peak oil, these theories collectively enhance our understanding of the complex interactions between economic growth, resource use, and environmental sustainability. By integrating these various approaches, we can develop more effective strategies to address the pressing challenges of our time, ensuring a balanced and sustainable future for generations to come.

3.3.2. Empirical evidence on the dynamic impact of energy policies

Energy policies are crucial in shaping the trajectory of economic growth and environmental protection. They determine the types of energy sources utilized, the efficiency of energy consumption, and the levels of greenhouse gas emissions. Renewable energy policies, for instance, focus on promoting the adoption of renewable energy sources such as wind, solar, and hydroelectric power. These policies often include financial incentives, subsidies, and regulations aimed at reducing the dependency on fossil fuels. Numerous studies have highlighted the positive environmental impacts of renewable energy policies. For example, Jacobson et al. (2017) demonstrate that a transition to 100% renewable energy by 2050 could significantly reduce air pollution and greenhouse gas emissions, thereby mitigating climate change and improving public health.

The economic impacts of renewable energy policies are equally significant. Renewable energy policies can stimulate economic growth by creating jobs and fostering technological innovation. Studies by Wei et al. (2010) and Moreno & López (2008) suggest that investments in renewable energy generate more employment opportunities compared to investments in fossil fuels. Moreover, the development and deployment of renewable energy technologies can drive economic diversification and reduce energy import dependency, enhancing energy security. Despite these benefits, the transition to renewable energy entails substantial initial costs and requires significant infrastructural changes. Sovacool (2009) argues that the high upfront costs and technological uncertainties associated with renewable energy projects can pose financial challenges, particularly for developing countries. Additionally, the intermittency of renewable energy sources such as wind and solar necessitates investments in energy storage and grid management technologies, further increasing the financial burden.

Fossil fuels have historically been the backbone of industrial development and economic growth. They are often more affordable and readily available compared to renewable energy sources, making them an attractive option for many countries. However, the volatility of fossil fuel prices and the geopolitical risks associated with fossil fuel dependency pose significant economic challenges. For example, Hamilton (2009) discusses the economic risks of oil price shocks and their implications for global economic stability. The environmental impacts of fossil fuel-based energy policies are numerous and severe. The extraction, transportation, and combustion of fossil fuels are major sources of air and water pollution, greenhouse gas emissions, and habitat destruction. Studies such as those by Epstein et al. (2011) and Haines et al. (2006) provide comprehensive assessments of the environmental and health impacts of coal mining and combustion, highlighting the need for stricter regulations and the transition to cleaner energy sources.

Energy efficiency policies aim to reduce energy consumption through technological improvements and behavioral changes. These policies can lead to significant economic savings by lowering energy bills and reducing the need for energy imports. Furthermore, improving energy efficiency can enhance industrial competitiveness and contribute to economic growth. For example, Geller et al. (2006) highlight that energy efficiency improvements in the industrial sector can reduce production costs and increase productivity. The environmental benefits of energy efficiency policies are also well-documented. By decreasing energy consumption, these policies can reduce greenhouse gas emissions and mitigate climate change. Moreover, energy efficiency measures can alleviate pressure on natural resources and reduce environmental degradation. For instance, Ürge-Vorsatz et al. (2012) demonstrate that energy efficiency improvements in buildings can lead to substantial reductions in energy demand and associated emissions.

Nuclear power is often touted as a low-carbon energy source that can provide a stable and large-scale supply of electricity. Studies such as those by Sovacool (2008) and McCombie and Jefferson (2016) examine the potential of nuclear energy to contribute to climate change mitigation and energy security. However, the high costs of nuclear power plants, concerns about nuclear accidents, and issues related to radioactive waste management pose significant challenges. The environmental and health impacts of nuclear accidents, as illustrated by the Chernobyl & Fukushima disasters, underscore the risks associated with nuclear energy. International trade and investment dynamics significantly influence the energy-economic-environmental nexus. Trade policies can affect the availability and competitiveness of energy technologies, while foreign investments can facilitate the transfer of energy technologies and capital. For instance, Dechezleprêtre et al. (2011) discuss how trade and investment policies can enhance the diffusion of clean energy technologies and contribute to global efforts to combat climate change.

Policy frameworks at the national and international levels play a crucial role in shaping the energy-economic-environmental landscape. National policies, including regulations, incentives, and subsidies, can drive the adoption of specific energy technologies and practices. International agreements and collaborations, such as the Paris Agreement, provide a platform for coordinated global action on climate change and energy transition. Studies by Rogelj et al. (2016) and Falkner (2016) highlight the importance of international cooperation and policy coherence in achieving sustainable energy and climate goals.

Empirical studies on energy consumption and economic growth often employ Granger causality tests to determine the direction of causality between these two variables. The results vary by region and time, reflecting the complexity of this relationship (Ozturk, 2010). Co-integration analysis is another common technique used to analyze the long-term equilibrium relationship between energy consumption and economic growth. These studies frequently find a positive long-term relationship, indicating that energy consumption and economic growth move together over time (Stern, 2011). Panel data studies, which leverage data from multiple countries over several years, are also prominent in this field. These studies can control country-specific effects and provide robust empirical evidence on the relationship between energy consumption, environmental factors, and economic growth (Apergis & Payne, 2009).

Empirical studies on the environmental impact of economic activities reveal a strong link between economic growth and CO2 emissions. Research indicates that industrial activities, transportation, and energy production are major sources of emissions, with policy interventions being crucial to mitigate these impacts (Shahbaz et al., 2013). The transition to renewable energy sources is another key area of empirical research. Studies in this domain explore the drivers and barriers to renewable energy adoption, such as economic incentives, technological advancements, and policy frameworks (REN21, 2019). Evaluating the impact of environmental policies on energy consumption and economic activities is critical, with empirical studies assessing the effectiveness of policies like carbon taxes, emissions trading systems, and renewable energy subsidies in achieving environmental and economic goals (Aldy & Stavins, 2012).

The environmental impacts of battery production have also been a focus of recent research. Wang et al. (2019) conducted an energy-environment-economy analysis of lithium-ion battery production in China, highlighting significant energy consumption and pollutant emissions during the production phase. Their research emphasized the importance of cleaner production practices and increased investments in environmental protection to promote sustainable development in the battery manufacturing sector. The study provided detailed insights into the carbon footprints of different battery types, underscoring the need for comprehensive evaluations of industrial processes (Wang et al., 2019). In a similar vein, Jia and Lin (2022) introduced the CEEEA2.0

model, a dynamic computable general equilibrium (CGE) model designed for energy-environment-economy analysis. This model integrates data and code availability, providing a robust framework for analyzing the impacts of energy policies on economic and environmental outcomes. The CEEEA2.0 model allows researchers to simulate various policy scenarios and assess their long-term effects on the energy-environment-economy nexus (Jia & Lin, 2022).

The integration of photovoltaic (PV) and energy storage systems (ESS) in buildings is another important area of research. Li et al. (2023) evaluated the integration of PV and ESS in residential buildings in Shenzhen, China, demonstrating that combining PV and battery systems significantly reduces energy consumption and carbon emissions. However, the study also noted the long payback periods and high carbon cost ratios associated with these technologies. The research highlighted the economic viability of integrating PV with ice storage systems, offering valuable insights for sustainable building design and policymaking (Li et al., 2023). Visualization techniques are also being used to analyze research trends in the energy-environment-economy field. Kao et al. (2022) used CiteSpace to conduct a bibliometric and visual analysis of research over the past two decades, identifying key research characteristics, hotspots, and evolution trends. Their analysis revealed a growing interest in systemic issues, environmental and climate change, and the increasing influence of Chinese research institutions. The study provided a comprehensive overview of the research landscape, guiding future research directions and methodologies (Kao et al., 2022).

Urban population density and its impact on the energy-environment-economy nexus have also been studied. Suzuki and Nijkamp (2020) explored the role of high urban population density in facilitating energy-environment-economy performance. Using data envelopment analysis, their study developed an autoconfiguration target model to assess the impact of urbanization on the energy-environment-economy nexus. The findings suggested that higher population densities could enhance performance by promoting efficient energy use and reducing environmental impacts. This research underscored the importance of urban planning and policy interventions in achieving sustainable urban development (Suzuki & Nijkamp, 2020).

The dynamics of the energy-economic-environmental impacts of different energy policies are complex and interdependent. Renewable energy policies offer significant environmental and economic benefits but face initial costs and technological integration challenges. Energy efficiency policies provide a cost-effective means of reducing energy consumption and emissions while enhancing economic productivity. Fossil fuel-based energy policies, while economically attractive in the short term, pose substantial environmental and economic risks. Nuclear energy presents a low-carbon alternative but comes with high costs and safety concerns. The interplay of these policies with international trade, investment, and policy frameworks further complicates the landscape. Addressing these challenges requires a holistic and coordinated approach that considers the multifaceted impacts of energy policies on economic development and environmental sustainability.

Empirical studies reveal mixed evidence on the macroeconomic impacts of energy infrastructure investments. Calderón, Moral-Benito, and Servén (2015) find that the growth effects of infrastructure depend on the quality of governance and the efficiency of public expenditure. In contexts where corruption and inefficiency are prevalent, the returns on infrastructure investments are significantly lower. This aligns with the findings of Pritchett (2000), who argues that the mere accumulation of infrastructure does not guarantee economic growth; rather, its productive utilization is key.

Another critical issue is the temporal dimension of these investments. R&D and infrastructure investments often yield benefits over long horizons, necessitating sustained policy commitment. Aghion et al. (2005) emphasize the role of institutional frameworks in fostering long-term innovation and investment. Their work highlights the importance of policy stability, intellectual property rights, and financial markets in supporting R&D-driven growth. Similarly, Esfahani and Ramírez (2003) demonstrate that the impact of energy infrastructure on economic performance is mediated by institutional quality and policy coherence.

The global energy transition adds urgency to increasing investments in R&D and energy infrastructure. McCollum et al. (2018) argue that achieving the Sustainable Development Goals (SDGs) requires unprecedented levels of investment in clean energy R&D and infrastructure. Their analysis suggests that integrating energy investments with broader development strategies can amplify their macroeconomic impact. For instance, electrification programs that prioritize rural and underserved areas not only enhance energy access but also stimulate local economic activity and reduce inequality, as documented by Dinkelman (2011).

Technological advances and digitalization further enhance the potential of R&D and energy infrastructure investments. Brynjolfsson & McAfee (2014) highlight how digital technologies can optimize energy systems, improving efficiency and reducing costs. Smart grids, for instance, enable real-time energy management, enhancing the reliability and sustainability of electricity distribution. These innovations underscore the complementarity between R&D and physical infrastructure investments, as advancements in one domain often unlock new opportunities in the other.

However, the distributional impacts of these investments warrant careful consideration. Stiglitz (2012) warns that technological change, while a growth driver, can exacerbate inequality if its benefits are not widely shared. This concern is particularly relevant in the context of energy infrastructure, where access disparities persist across regions and income groups. Policies to ensure equitable access to energy and the benefits of technological progress are essential for maximizing the inclusive growth potential of these investments.

Finally, the global experience with energy crises and economic shocks underscores the importance of resilience in energy infrastructure and systems. R&D investments in energy storage, grid modernization, and renewable technologies are crucial for enhancing resilience, as highlighted by Sovacool (2017). These investments not only mitigate the economic impacts of energy disruptions but also strengthen the capacity of economies to adapt to climate change and other systemic risks.

In conclusion, increasing investments in R&D and physical infrastructure for electricity and gas production and distribution offers significant macroeconomic benefits, but these benefits are contingent on various factors, including institutional quality, policy coherence, and equitable distribution. Theoretical and empirical studies consistently highlight the transformative potential of these investments in fostering sustainable, inclusive, and resilient economic growth. However, realizing this potential requires addressing financing, governance, and temporal alignment challenges. As global economies navigate the twin imperatives of development and decarbonization, the integration of R&D and energy infrastructure investments into broader economic strategies will be critical for achieving long-term prosperity.

3.4. Methodology to simulate the impacts of the energy policies in Togo

Theoretical frameworks and methodologies are essential for analyzing the dynamic interactions between energy, environment, and economy. These frameworks provide structured approaches to model complex systems, evaluate policy impacts, and predict future trends. System dynamics models, for example, use feedback loops, stocks, and flows to simulate the behavior of complex systems over time, making them particularly useful for understanding the non-linear interactions and potential tipping points in the energy-environment-economy nexus (Sterman, 2000). An example of this is the Limits to Growth model by Meadows et al. (1972), which used system dynamics to project the consequences of exponential economic and population growth in a world of finite resources.

Environmental Input-Output Analysis extends traditional input-output models by incorporating environmental factors, allowing for the assessment of the environmental impacts of economic activities and the identification of key sectors contributing to environmental degradation (Leontief, 1970). Multi-regional input-output models analyze economic and environmental interactions across multiple regions, accounting for trade and the distribution of environmental impacts (Wiedmann et al., 2011). These models have been applied to various contexts, such as assessing the economic consequences of climate policies in the European Union or evaluating the effects of renewable energy subsidies in China (Zhang et al., 2013).

Econometric models offer another powerful methodology. Time-series econometric models analyze data over time to identify trends, cycles, and relationships between variables and are used to study the long-term relationship between energy consumption, economic growth, and environmental impact (Stern, 2004). Panel data econometric models combine cross-sectional and time-series data to control individual heterogeneity and provide more robust estimates and are widely used in empirical studies on the energy-environment-economy nexus (Baltagi, 2005). Integrated assessment models (IAMs) combine climate science and economic analysis to evaluate the costs and benefits of climate policies. These models help in understanding the trade-offs between economic growth and climate mitigation (Nordhaus, 1994). Energy-economy models integrate energy system models with economic models to assess the impacts of energy policies on economic performance and environmental outcomes. These models are used to study scenarios such as the transition to renewable energy or implementing carbon pricing (Paltsev et al., 2005).

Behera & Mishra (2019) and Solarin & Bello (2021) investigate the possibility of switching the fossil fuels of oil, coal, and natural gas for renewable energy and underline the relationship between this shift and economic growth. Locking, for the potential impact on jobs, UNDP, (2021a) developed and tested the Green Jobs Assessment Modelling (GJAM) in the case of Zimbabwe and Nigeria. This model is dynamic top-down and allows for the assessment of indirect and induced impacts of the energy transition scenarios. Therefore, different scenarios in the energy transition in Togo will be simulated using EPLAN software, which will use electricity capacity and demand, heating and mobility energy generation, and consumption. After getting the optimal share of RE and non-RE this scenario will be used in GJAM to simulate the socio-economic impacts. However, this model requires the absolute minimum of data such as the Input-output table, the time series of the system of national accounts, and the employment and emissions data by industry.

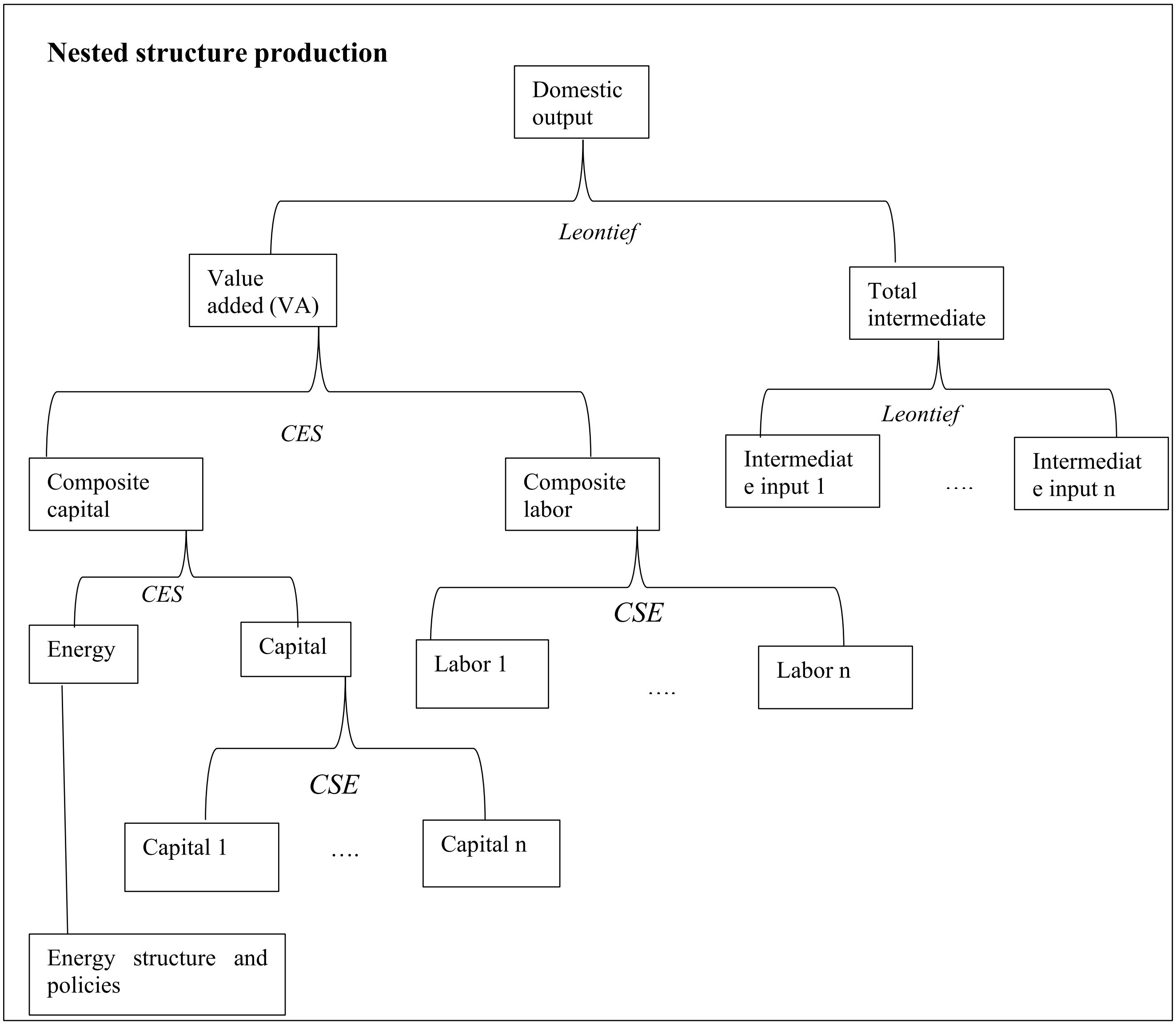

Figure 21: Nested structure production for the dynamic CGE model
Source: Adapted by Decaluwe et al., (2009)

This chapter relies on the computable general equilibrium model (CGE) adapted by Decaluwe et al. (2009) (**Figure 21**). The model is a dynamic computable general equilibrium (CGE) model designed to analyze national economies. It operates within a general equilibrium framework, assuming market equilibrium across goods, services, and factor markets. The model incorporates microeconomic foundations where firms maximize profits and households maximize utility, with price-taking behavior in competitive markets. The production process is modeled using a nested structure: at the top level, output combines value-added and intermediate inputs via Leontief technology, while value-added itself is a CES function of labor and capital. Different types of labor and capital are modeled as imperfect substitutes using CES functions. Household consumption is driven by Stone-Geary utility functions, resulting in a Linear Expenditure System (LES) that provides flexibility in substitution and income elasticities.

The model includes a detailed representation of fiscal mechanisms, allowing for taxes on labor, capital, production, and products, as well as transfers among households, firms, government, and the rest of the world. International trade relations adopt the small-country hypothesis, with world prices exogenously set, and trade flows modeled using CET functions for export-domestic supply and CES functions for import-domestic consumption. Equilibrium conditions ensure that goods and factor markets balance through price adjustments, while the savings-investment balance determines capital formation. Calibration relies on a Social Accounting Matrix (SAM) to ensure consistency between macroeconomic aggregates and inter-institutional transactions. Prices incorporate taxes, margins, and world market conditions, with multiple indexes like the GDP deflator and CPI computed for analysis.

The model is calibrated using baseline SAM data and elasticity parameters drawn from econometric studies or literature. It can simulate the impact of policy changes, such as fiscal reforms, trade adjustments, or external shocks, on economic indicators like GDP, household income, and consumption. This makes the model a comprehensive tool for policy analysis and resource allocation studies. The model is based on GAMS software using the Non-linear Problem (NLP) solver. It consists of six blocks: production block, incomes and savings block, demand block, trade block, market-clearing and macroscopic closure block, and macro-indicator block.

Following Jia & Lin (2022), we consider the PEP-1-t model which is the 7-tier nested production technology. The other input parts are CES production technology except that Leontief production technology is applied to the aggregated intermediate input. The production process in the PEP-1-t model is structured hierarchically using a nested framework. The mathematical structure of the model is deeply detailed in the Appendix.

At the top level, aggregate output combines value-added and intermediate inputs using a Leontief production function, which assumes no substitutability. Value-added is composed of composite labor and capital, linked via a constant elasticity of substitution (CES) function, which allows for some substitutability. At the bottom level, labor and capital are further disaggregated into types, each also combined using CES functions. Intermediate consumption comprises various goods and services combined in fixed proportions. The model captures the cost-minimizing behavior of firms in choosing input combinations based on relative prices.

Income generation and savings are analyzed across households, businesses, the government, and the rest of the world. Households derive income from labor, capital, and transfers, and allocate it between consumption, savings, and taxes. The model accommodates varying marginal propensities to save. Business incomes are derived from capital returns and transfers, with taxes subtracted to yield disposable income. Government revenues stem from various taxes (on income, production, and imports) and capital returns, while expenditures include transfers and public consumption. The rest of the world interacts through trade and transfers, with net savings reflecting the current account balance.

Demand for goods and services includes household consumption, investment, government spending, and margins (trade and transport). Household consumption is modeled using a Stone-Geary utility function, which allows for subsistence consumption and variable elasticities. Investment demand, split into gross fixed capital formation (GFCF) and inventory changes, is endogenous and price sensitive. Government demand for goods is similarly determined based on a fixed budget and prices. Intermediate and margin demands depend on production and trade volumes, respectively.

Producers allocate their output between products and markets using CET functions, reflecting imperfect transformability among products and markets. Exports and domestic supply are modeled based on revenue maximization, with the small-country hypothesis assuming exogenous world prices. Domestic demand integrates imports and local products via CES aggregation, indicating imperfect substitutability. The model accommodates price responsiveness for both imports and exports, reflecting elasticity conditions.

Price determination in the model incorporates both cost-based and market-based elements. Aggregate prices are weighted averages of component prices, adjusted for taxes and margins. Production prices include taxes on production and factor use. Prices of composite commodities reflect domestic and import sources, adjusted for taxes and exchange rates. The model also defines key price indices, including the GDP deflator, consumer price index, investment price index, and government expenditure price index, to analyze inflationary dynamics.

The model ensures equilibrium in goods, factors, and savings-investment markets. Supply equals demand for all commodities, labor, and capital. Investment is equated with aggregate savings, which includes contributions from households, businesses, government, and the rest of the world. These conditions are essential for achieving a consistent general equilibrium solution. GDP is calculated from three perspectives: production, expenditure, and income. GDP at basic prices sums payments to factors and production taxes. GDP at market prices includes taxes on products and imports. From the expenditure side, GDP aggregates net final expenditures (consumption, investment, and net exports). The model links these GDP concepts to align with national accounting standards, offering a comprehensive measure of economic activity.

3.4.1. The simulation scenarios

The simulation scenarios explore the impact of varying levels of R&D and physical investments in the electricity and gas production and distribution sectors. Five distinct scenarios are analyzed to understand their individual and combined effects. In Scenario 1, an increase of 1% in R&D investment is made without any additional physical investment, focusing solely on technological innovation. Scenario 2 emphasizes physical infrastructure, with an increase of 1% in investment in this area and no R&D spending. Scenario 3 combines equal levels of investment, allocating 1% to both R&D and physical infrastructure to evaluate the synergy between technological advancements and infrastructure improvements. Scenario 4 significantly increases the stakes, with 5% invested in both R&D and physical infrastructure, simulating a more ambitious development strategy. Finally, Scenario 5 represents the highest level of investment, with 10% allocated to both R&D and physical infrastructure, examining the effects of aggressive financial commitment to innovation and capacity expansion. These scenarios provide a comprehensive framework to assess strategic investments in the energy sector and their implications for production and distribution efficiency.

The chosen scenarios reflect realistic and strategic variations in investment priorities to assess their individual and combined impacts on the energy sector. By isolating R&D (Scenario 1) and physical infrastructure (Scenario 2), the analysis reveals the unique contributions of innovation versus capacity. Scenario 3 tests synergy effects, while Scenarios 4 and 5 explore the scalability of benefits from higher investments. This structured escalation, from minimal to aggressive investments, mirrors actual policy options and budget constraints, providing valuable insights into cost-effective strategies for improving energy production and distribution. The scenarios are thus designed to guide informed decision-making in energy planning and development.

3.4.2. The social accountable matrix and model calibration

Togo's 2018 Social Accounting Matrix (SAM), a technique related to national income accounting, provides a conceptual basis for examining the growth and distributional issues within a single analytical framework in an economy that is used to calibrate the model. It can be seen as a means of presenting the interaction between production, income, consumption, and capital accumulation in a single matrix. A SAM is defined as the presentation of System of National Accounts (SNA) accounts in a matrix that elaborates the linkages between a supply and use table and institutional sector accounts. In many instances, SAMs have been applied to an analysis of interrelationships between structural features of an economy and the distribution of income and expenditure among household groups. SAMs are closely related to national accounts, whereby their typical focus on the role of people in the economy may be reflected by, among other things, extra breakdowns of the household sector and a disaggregated representation of labour markets (i.e., distinguishing various categories of employed persons). On the other hand, SAMs usually encompass a somewhat less detailed supply and use table or input-output table.

The dynamic Computable General Equilibrium (CGE) model is structured over a discrete time horizon, represented by the set T, which spans ten annual periods from 2018 to 2027. This periodization allows for tracking the evolution of economic variables over time. The model starts in 2018, which serves as the benchmark year and is directly based on the 2018 Social Accounting Matrix (SAM). The first period, denoted as T1(t), corresponds to this base year and provides the initial conditions for the simulation. The time set T is further subdivided to facilitate the interpretation of results across different phases of the simulation. The initial years (2018 and 2019) are grouped as tt1(t), representing the starting phase of the model. The years 2020 to 2025 form the intermediate phase, tt2(t), where most medium-term policy impacts and structural adjustments are analyzed. The final phase, tt3(t), includes 2026 and 2027, which are used to observe the long-term effects and the model's convergence behavior. A specific subset, ttt1(t), includes the boundary years 2018, 2019, 2026, and 2027, often used to compare the initial and final states of the system.

This time framework enables the model to simulate dynamic changes and assess the impact of various economic policies or external shocks over time.

The SAM is a comprehensive, flexible, and disaggregated framework that elaborates and articulates income generation by production activities and the distribution and redistribution of income between social and institutional groups. A principal objective of compiling a SAM is to reflect various interdependencies in the socio-economic system by recording, as comprehensively as is practicable, the actual and imputed transactions and transfers between various agents in the system. The 2018 Togo SAM contains production activities, factors of production, and institutions.

3.5. Results and discussions

3.5.1. Impact on total investments

3.5.1.1. Dynamic of investments in the base scenario

F**igure 22** illustrates the dynamics of investments (millions CFA) in the base scenario, devoid of any energy policy interventions, with a clear delineation between total, private, and public investments over ten years. Across the timeframe, there is a consistent upward trend in total investments, increasing from 742,514 in year 1 to 887,050.2 in year 10. This growth suggests a stable and progressive economic environment, fostering both private and public sector investments.

Private investments dominate the composition of total investments, accounting for a significant share each year. They begin at 652,212.4 in year 1 and steadily rise to 774,710.2 in year 10, highlighting the pivotal role of private sector activity in driving economic growth under the base scenario. The continuous increase may reflect favorable conditions for private sector initiatives, such as stable market environments or attractive returns on investment.

Public investments, though relatively smaller in magnitude, also show a consistent upward trajectory, increasing from 35,615.55 in year 1 to 42,994.48 in year 10. This steady growth underscores a commitment to public sector expenditure, which likely supports infrastructure development, social services, and other public goods critical to sustaining the broader investment climate.

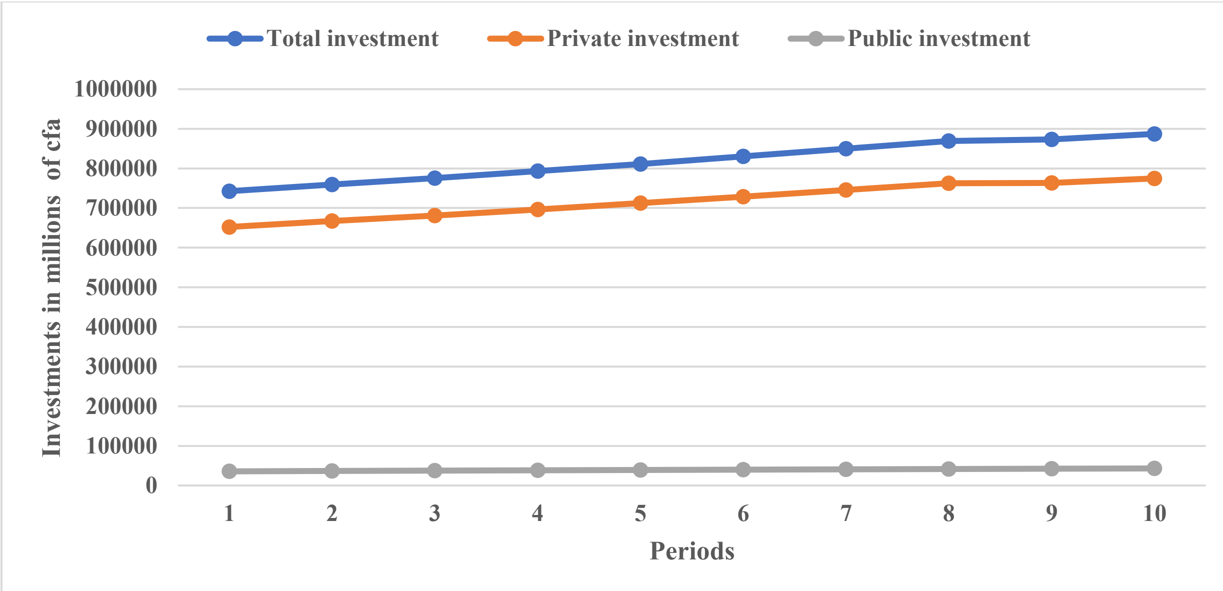

Figure 22: Dynamics of investments in the base scenario

A slight deceleration in the growth rate of total investments is observed towards the later years, particularly between years 8 and 9, where the total investment increases marginally from 869,291.7 to 873,410.3. This could indicate the onset of diminishing returns or constraints within the economic framework that may limit further investment expansion. Overall, the interplay between private and public investments suggests a complementary relationship, where public investments potentially play a facilitative role in creating an enabling environment for private sector activities. The base scenario paints a picture of a growing economy, with balanced contributions from both sectors, albeit with private investments leading the charge.

3.5.1.2. Dynamic of investments' variation in different simulation scenarios

Figure 23 reflects the dynamics of total investment variations in percentage under different simulation scenarios involving incremental increases in Research and Development (R&D) and Physical Investment (IP) specifically in the electricity and gas production and distribution sectors. These variations are analyzed for the five scenarios. Across all scenarios, the data reveals a general trend of positive but varying degrees of investment impact. Overall, the Figure supports the argument that balanced and substantial investments in R&D and IP are necessary to drive meaningful advancements in the energy sector, particularly in electricity and gas production and distribution. The findings resonate with recent literature that underscores the dual importance of technological innovation and infrastructure development in transitioning toward sustainable and resilient energy systems.

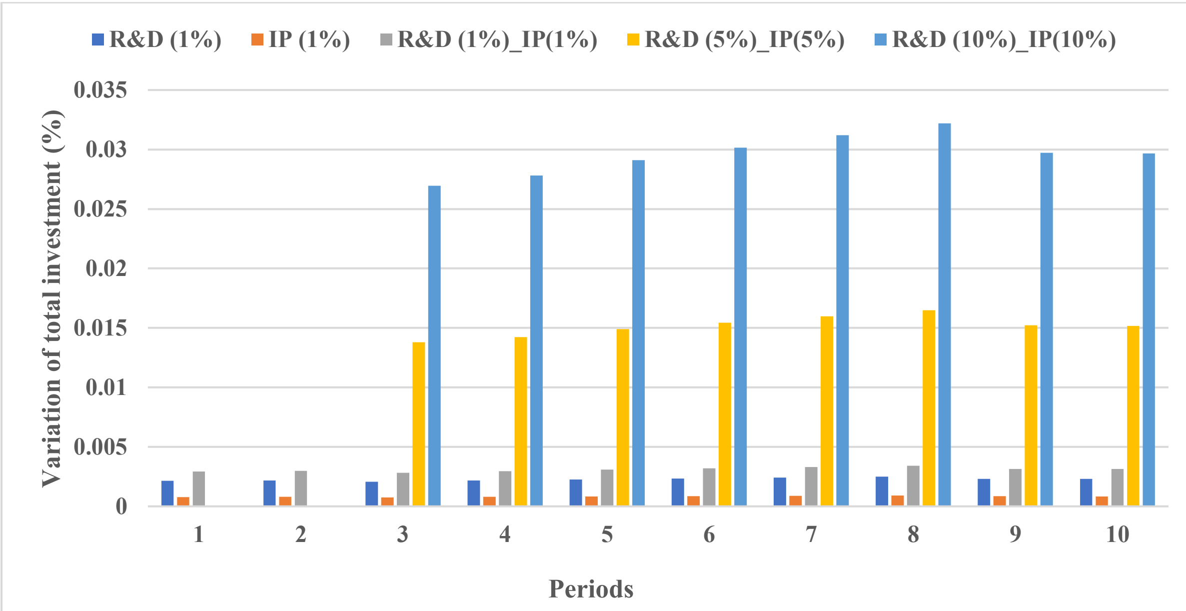

Figure 23: Dynamic of total investment variations in percentage

When R&D or IP is increased individually at 1%, the variations are modest, reflecting the relatively small influence of isolated efforts in improving investment dynamics. For instance, variation in the R&D (1%) scenario begins at 0.00214 in period 1 and peaks at 0.002501 in period 8, indicating a slow but steady impact over time. Similarly, for IP (1%), variations are even smaller, ranging from 0.000785 in period 1 to 0.000917 in period 8. In the combined R&D (1%) and IP(1%) scenario, the variations are slightly higher than when the factors are implemented independently, peaking at 0.003418 in period 8. This indicates a synergistic effect of combining moderate increases in R&D and IP, consistent with findings in recent literature highlighting the complementary roles of technological innovation and physical infrastructure in advancing the energy sector.

The dynamics of private investment variations across simulation scenarios highlight the influence of Research and Development (R&D) and Physical Investment (IP) on the electricity and gas sectors (**Figure 24**). Incremental increases in R&D or IP at 1% produce modest variations, reflecting limited capacity to significantly stimulate private sector contributions. For instance, the R&D (1%) scenario sees variations rise from 0.002278 in period 1 to 0.002704 in period 8, while

IP (1%) peaks at 0.000991 in the same period. These results indicate that small, isolated increases, though positive, lack the scale to drive substantial private-sector responses.

In contrast, combining R&D and IP at 1% yields slightly higher variations, peaking at 0.003418 in period 8. This underscores the complementary nature of technology and infrastructure investments, where integrated approaches amplify private sector impacts. More ambitious scenarios, such as R&D (5%) and IP (5%) and R&D (10%) and IP (10%), show substantial increases, with private investment variations peaking at 0.034789 in period 8 under the R&D (10%) and IP (10%) scenario. These scenarios demonstrate the transformative potential of coordinated, aggressive investments in fostering innovation, reducing costs, and expanding infrastructure.

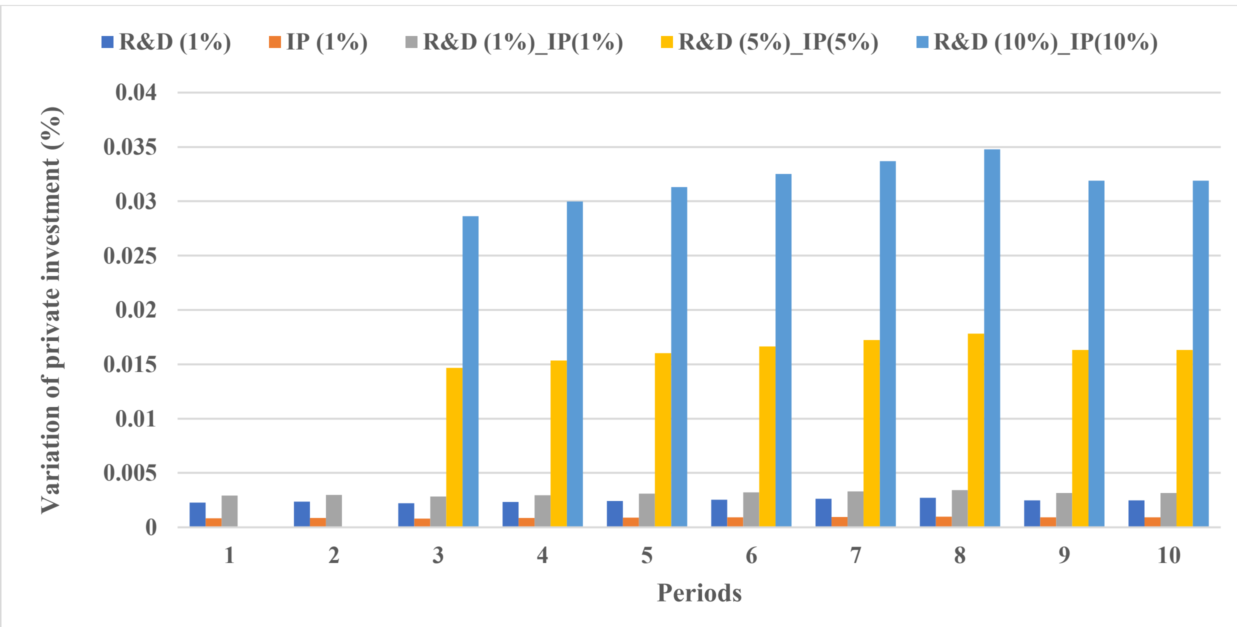

Figure 24: Dynamic of private investment variations in percentage

The dynamics of public investment variations across different simulation scenarios highlight the impact of Research and Development (R&D) and Physical Investment (IP) on the electricity and gas sectors. Under individual increases of R&D (1%) or IP (1%), variations in public investments remain modest, with the R&D (1%) scenario starting at 0.001479 in period 1 and peaking at 0.001511 in period 8, while IP (1%) begins at 0.000542 in period 1 and peaks at 0.000554 in period 8. These results suggest that isolated, small-scale increases in R&D or IP have limited effects on public investment variations, reflecting their inability to address systemic challenges in infrastructure and innovation comprehensively.

In the combined R&D (1%) and IP (1%) scenario, public investment variations are slightly higher, peaking at 0.002064 in period 8. This indicates a synergistic effect where moderate, integrated investments yield better outcomes than isolated efforts. However, significant increases, as seen in the R&D (5%) and IP (5%) and R&D (10%) and IP (10%) scenarios, lead to transformative impacts, with variations peaking at 0.010017 and 0.019566, respectively, in period 8. These scenarios demonstrate the critical role of coordinated, high-level investments in fostering public sector contributions to innovation and infrastructure expansion.

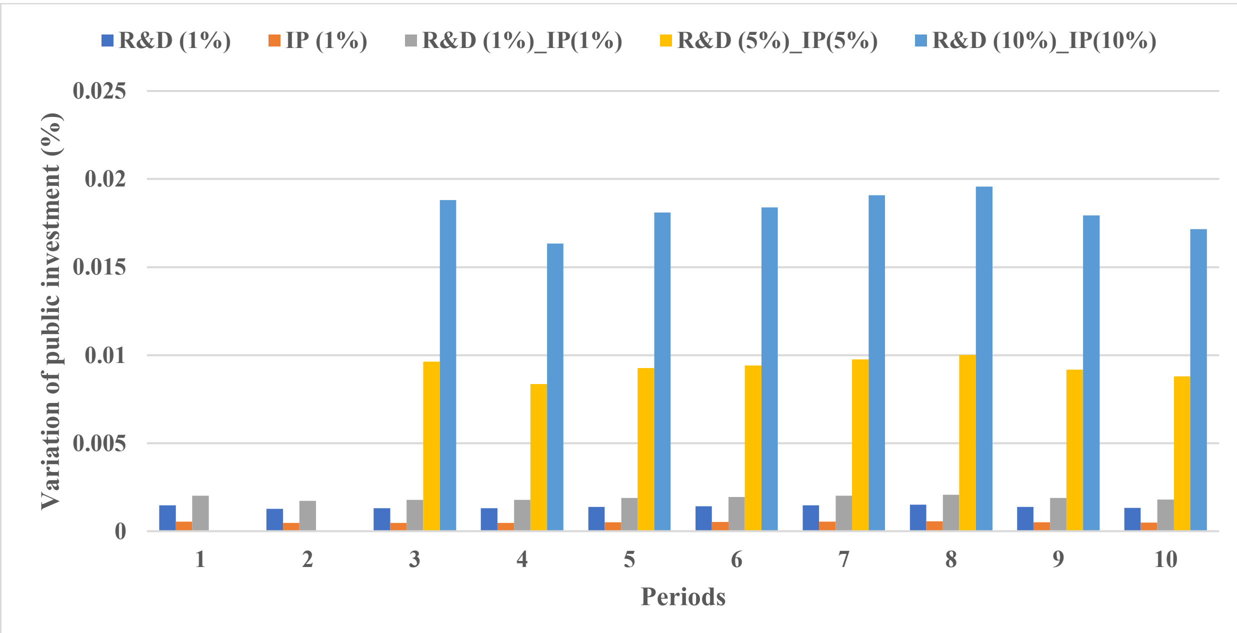

Figure 25: Dynamic of public investment variations in percentage

The dynamics of investment variations in different scenarios highlight the significant interplay between Research and Development (R&D) and Physical Investment (IP) in advancing the electricity and gas production and distribution sectors. These findings align with recent literature emphasizing the critical role of targeted investments in achieving energy sustainability, efficiency, and resilience. The modest impact of a 1% increase in R&D or IP reflects the limited efficacy of incremental investment strategies. While minor increases in R&D can improve operational efficiencies and reduce costs in the long term, they are insufficient to drive transformational changes in energy systems. Similarly, small increments in IP alone may fail to leverage advanced technologies, creating a gap between infrastructure capabilities and emerging energy demands. Studies such as those by Wang et al. (2022) emphasize that coupling R&D with physical investments is essential to amplify their impacts and catalyze broader sectoral advancements.

The synergistic effects observed in scenarios combining R&D and IP at 1% highlight their complementarity. The co-evolution of technology and infrastructure leads to exponential returns on investment, as R&D enhances the efficiency and cost-effectiveness of infrastructure while IP ensures the deployment of these innovations at scale. For instance, the slightly higher investment variations in combined moderate scenarios suggest that even modest coordinated efforts yield better outcomes than isolated investments. However, the substantial impact observed in high-investment scenarios, such as combined increases of 5% and 10%, underscores the transformative potential of aggressive strategies. These scenarios reflect how substantial R&D investments foster breakthroughs in renewable technologies, grid management, and energy storage, while large-scale IP enables their effective application.

Such high investments are pivotal for meeting global energy transition goals, as emphasized by the World Bank (2023) and IRENA (2022). Achieving net-zero emissions and enhancing energy access requires sustained, high-level funding for both technological advancements and physical infrastructure. The decline in investment variations in the final periods under high-investment scenarios may reflect saturation effects or the time lag in realizing the full benefits of these investments. This aligns with the principle of diminishing marginal returns, as noted by Nordhaus (2023), highlighting the importance of dynamically adjusting investment levels to optimize long-term outcomes.

These findings suggest that moderate investment strategies, while beneficial, are inadequate for addressing the multifaceted challenges of the energy sector. Coordinated and substantial investments are necessary to drive innovation, expand infrastructure, and achieve sustainability. This perspective aligns with Sovacool et al. (2022), who argue that energy transition strategies must prioritize integrated approaches combining innovation funding with infrastructure expansion. The analysis underscores the transformative potential of coordinated R&D and IP investments, particularly at higher levels. Evidence from this research and recent literature reinforces the need for ambitious and strategic investment frameworks to meet future energy demands, enhance resilience, and support global sustainability goals.

3.5.2. Impact of energy policies on different economic sectors' production

The dynamics of production (in millions CFA) across various economic sectors over 10 years in the base scenario illustrate significant growth trends and sectoral interdependencies (**Figure 26**).

As the largest contributor, agriculture consistently increases from 798,229 in year 1 to 1,019,201 in year 10, reflecting its central role in the economy and its ability to sustain growth without direct policy stimuli. Similar trends are observed in sectors such as food manufacturing, which grows steadily from 512,029 in year 1 to 601,657 in year 10, demonstrating its alignment with agricultural outputs and its role in value addition. Industries with high growth rates, such as construction, commerce, and transport, underscore the expanding infrastructure and trade activities. Construction, for instance, rises from 556,877 in year 1 to 684,025 in year 10, indicating ongoing urbanization and infrastructure development. Commerce and transport similarly show robust growth, driven by increasing consumer and logistical demand.

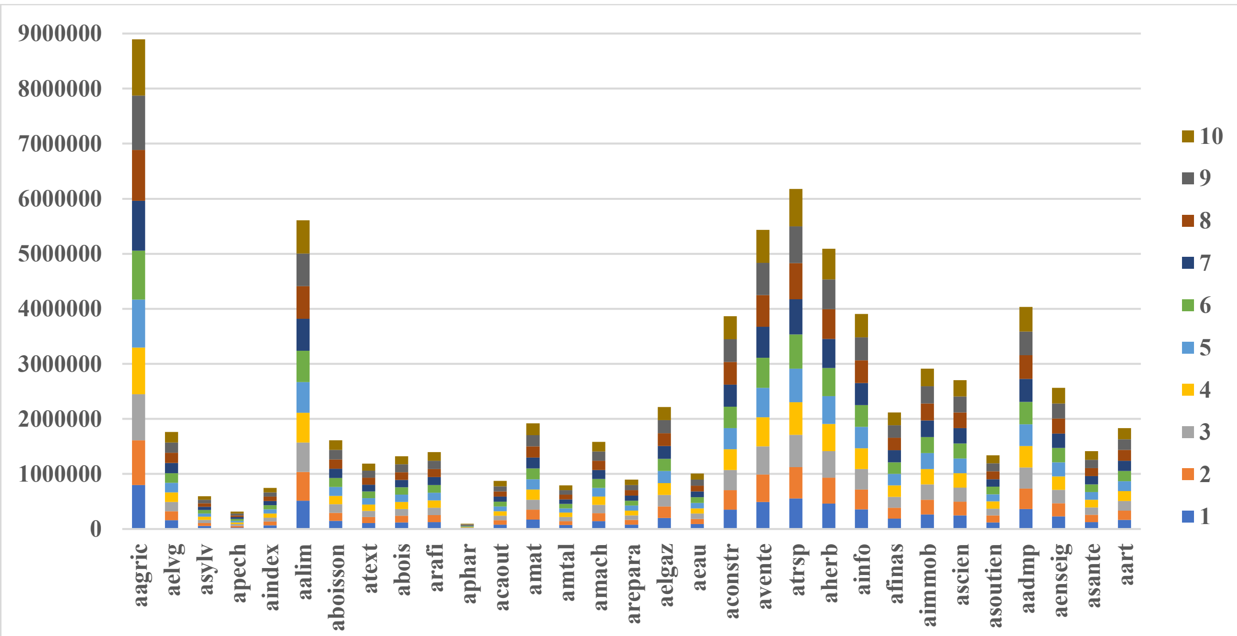

Figure 26: Dynamic of different economic sectors' production in the base scenario

On the other hand, smaller sectors like sylviculture, fishing, and textiles also exhibit steady but more modest increases, pointing to their dependence on larger industries or slower technological progress. Energy production and distribution sectors, such as electricity and gas, and water and waste management, also show growth aligned with increasing demand for utilities, reflecting the expansion of urban populations and industrial activities. Manufacturing sectors with higher value addition, including pharmaceuticals and chemical production, also see consistent gains, indicating gradual advancements in industrial diversification. However, extractive activities display slower growth, suggesting potential resource constraints or limited expansion without policy interventions.

These trends highlight a naturally expanding economy with agriculture and related sectors as the backbone, complemented by infrastructure development and industrialization. Without policy, however, sectors requiring innovation, such as textiles and high-tech manufacturing, may face limitations in achieving transformative growth. This underscores the importance of policy interventions to enhance sectoral productivity and address structural inefficiencies in key areas.

- ***Impact of investment in Research and Development (R&D) and Physical Investment (IP) on production of the public sector***

The impact of increased investment in Research and Development (R&D) and Physical Investment (IP) on public sector production, particularly in electricity and gas production and distribution, reveals mixed and marginal effects under the three scenarios analyzed (**Figure 27**). In the R&D (1%) and IP (1%) scenarios, the variations in public sector production oscillate between negative and positive impacts, with changes primarily in the range of -0.00022 to 0.00009 across the 10 periods. This suggests that isolated increases in R&D or IP alone have limited and inconsistent effects on public sector productivity, potentially due to the gradual nature of innovation uptake or infrastructure development.

In the combined R&D (1%) and IP (1%) scenario, the variations are slightly more positive but remain small, peaking at 0.000124 in period 10. This indicates a mild synergistic effect when R&D and IP investments are integrated, as advancements in technology and infrastructure complement each other to support public sector production. However, the overall impact remains marginal, reflecting the inherent constraints within the public sector, such as slower adaptability, regulatory hurdles, or inefficiencies that may limit the immediate productivity gains from investments.

Studies such as Sovacool et al. (2022) emphasize that the public sector often faces structural inefficiencies, including rigid bureaucratic processes, budget constraints, and slower adaptability to technological changes. These factors likely explain the marginal and inconsistent impacts of R&D and IP investments in this context. Additionally, Wang et al. (2021) note that the public sector often requires substantial, sustained investments to overcome inertia and achieve meaningful productivity gains, as opposed to the incremental 1% increases examined in this scenario.

The slight synergistic effect observed in the combined R&D and IP scenario aligns with findings by IRENA (2022), which suggest that integrated investments in innovation and infrastructure create better conditions for productivity improvements. However, the limited scale of the observed impacts underscores that 1% increases are insufficient to leverage the full potential of these synergies. High transaction costs, time lags in technology adoption, and the need for complementary policy frameworks are identified in the literature as significant barriers to maximizing the benefits of such investments.

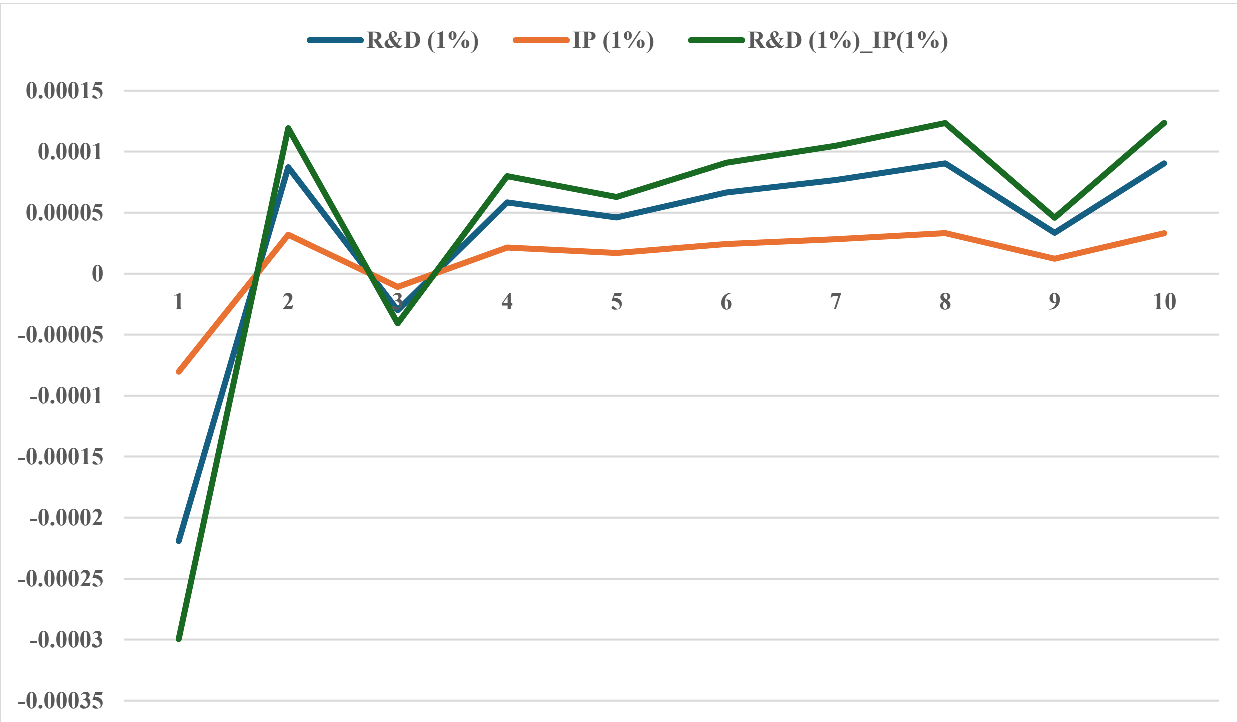

Figure 27: Impact of investment in Research and Development (R&D) and Physical Investment (IP) on public sector production

The oscillating effects, particularly negative variations in earlier periods, are consistent with the transitional costs identified by the World Bank (2023). Introducing new technologies or upgrading infrastructure often incurs initial disruptions or adaptation challenges before realizing longer-term gains. These findings support the need for patient capital and strategic planning to manage these transitional phases effectively.

To amplify the impact of R&D and IP on public sector production, Nordhaus (2023) advocates for scaling investments beyond incremental increases and combining them with structural reforms. This includes enhancing workforce skills, streamlining regulatory processes, and fostering partnerships with the private sector. Furthermore, the role of energy policy frameworks, such as targeted subsidies for green technologies or incentives for efficiency improvements, is critical in creating an enabling environment, as highlighted by IEA (2023)

3.5.3. Impact of energy policies on incomes and savings

3.5.3.1. Dynamic of incomes in the base scenario

Figure 28 outlines the income dynamics for various economic actors in Togo under a base scenario over ten years. It reflects gradual growth across all categories, pointing to a stable economic environment with incremental increases in income levels for firms, households, and other entities. The firm sector shows consistent growth, rising from 1,037,046 to 1,244,868. This indicates a steady expansion of private sector activities, which likely contributes to job creation and economic diversification. Such growth may be attributed to increased business investments, improved market access, or supportive government policies fostering entrepreneurship and industrial development. Government income also exhibits steady growth, from 962,314 to 1,163,826, reflecting an expanding revenue base, likely driven by economic growth, increased tax collection, or broader fiscal reforms. This trend underscores the government's potential to fund public services, infrastructure projects, and social programs, which are crucial for development. Employee household income stands out as the largest category, increasing from 1,442,840 to 1,767,983. This suggests a robust labor market with rising wages or employment opportunities. It indicates a strengthening middle class and higher purchasing power, which can stimulate domestic demand and contribute to economic growth.

The agricultural independent production sector (agrindp) grows from 856,606 to 1,015,781. Although its growth is steady, it remains relatively modest compared to other sectors. Agriculture remains a critical component of Togo's economy, employing a significant proportion of the population. However, the slower growth might signal challenges such as limited access to modern technologies, climate variability, or inefficiencies in the value chain. Non-agricultural independent production (indepnonagri) shows similar trends, increasing from 1,151,064 to 1,393,756. This reflects the significance of the informal sector and small-scale businesses in driving economic activities outside agriculture. Supporting this sector with better infrastructure, financial services, and market access could amplify its contribution to GDP.

Unemployment-related income (noemploi) shows an increase from 214,576 to 262,428. While this growth might reflect expanded social safety nets or support systems, it could also indicate persistent unemployment challenges. Policies aimed at creating jobs and fostering skills development are essential to address this issue. Finally, Institutions Serving the General Interest (ISBL) income grows from 48,163 to 57,884, remaining the smallest category. This sector's limited growth suggests a relatively minor role in the economy, potentially due to limited funding or focus on social and community-driven initiatives. Strengthening the capacity of these institutions could help address pressing social challenges and promote inclusive development.

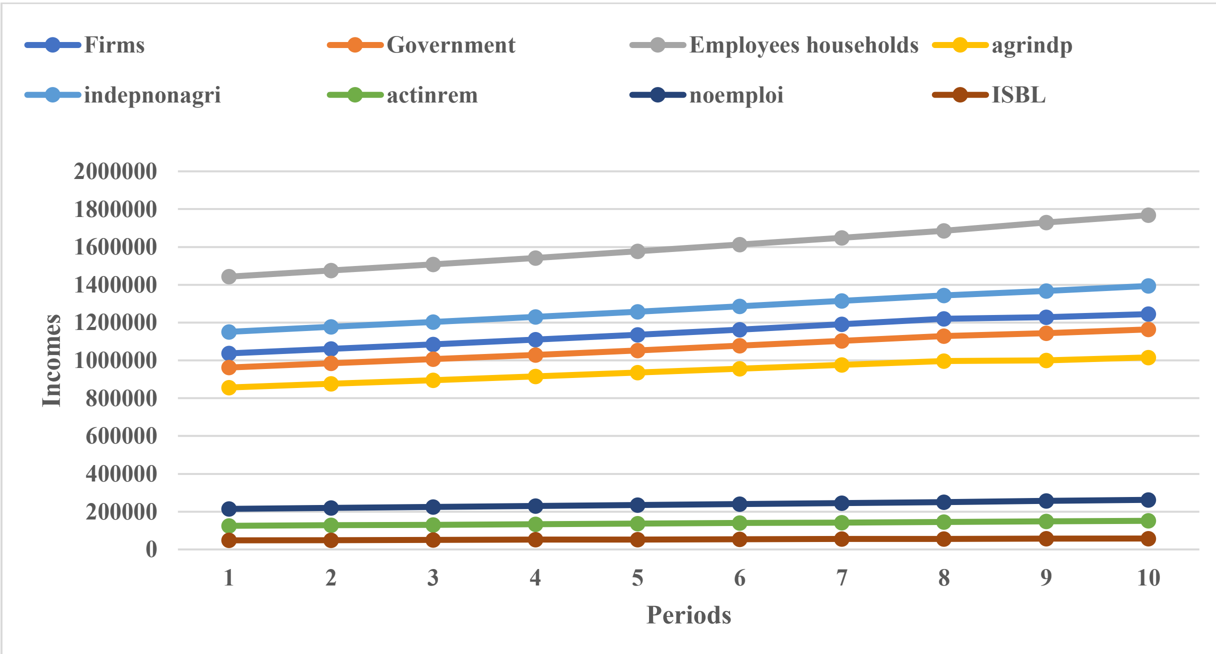

Figure 28: Incomes dynamics in the base scenario

In summary, the data portrays a generally positive trajectory for Togo's economy, with stable growth across sectors. However, the slower progress in agriculture, informal production, and social safety nets highlights areas requiring targeted interventions. Investments in infrastructure, technology, and human capital, alongside supportive policies, could help unlock the full potential of Togo's economy and ensure more equitable and inclusive growth.

3.5.3.2. Dynamic of the investment in research and development (R&D) impact on incomes

Figure 29 highlights the effects of increased investments in research and development (R&D) in electricity and gas production on incomes across various economic sectors in Togo. Overall, the findings align with scholarly insights on the transformative role of energy innovation in driving economic growth, fostering productivity, and promoting equitable development.

The income impact is most pronounced for firms and government revenues, peaking in Year 8. This reflects the direct influence of R&D on improving energy efficiency, reducing production costs, and enhancing industrial output. As Acemoglu et al. (2012) argue, technological innovation driven by R&D not only boosts productivity within industries but also creates spillover effects across the economy. In Togo, improved energy systems likely contribute to greater industrial competitiveness and increased fiscal revenues through taxation and reduced energy subsidies. The high-income growth for households, especially in Years 9 and 10, underscores the role of R&D in job creation and wage increases. This aligns with findings by Duflo and Pande (2007), who illustrate how energy infrastructure projects improve household incomes by fostering productivity and economic opportunities. The benefits here may stem from enhanced access to reliable energy, enabling businesses to grow and employ more workers.

Despite the positive impact, the growth rate for agriculture is modest. This may be attributed to structural barriers limiting the adoption of energy innovations in rural areas. Schmid and Rogge (2021) emphasize the need for sector-specific R&D policies, particularly in agriculture, to develop tailored solutions such as solar-powered irrigation and off-grid energy systems. Without these interventions, the full potential of energy R&D in transforming rural economies may remain untapped.

Figure 29: Dynamic of the investment in research and development (R&D) impact on incomes

The steady income growth in this sector reflects the importance of energy access for small and medium enterprises (SMEs). As Bloom et al. (2013) highlight, energy innovation reduces operating costs for businesses, improving their competitiveness and profitability. This is particularly critical for informal enterprises, which constitute a significant portion of Togo's economy. While the steady increase reflects indirect benefits of R&D, such as expanded social programs funded by increased government revenues, it also indicates persistent unemployment. Autor et al. (2020) argue that technology-driven growth must be complemented by active labor market policies to ensure inclusive job creation, particularly in regions with high unemployment rates. The smaller income impact on ISBL highlights the limited direct benefits of energy R&D for non-profit organizations. As Ostrom (1990) suggests, public-private collaborations can help extend the reach of technological innovation to address community-level challenges, such as access to education and healthcare.

Overall, the figure underscores the transformative potential of R&D in the energy sector, aligning with scholarly insights. However, the uneven distribution of benefits across sectors highlights the need for targeted strategies to ensure equitable impacts. Investments in education, training, and tailored energy solutions for underserved sectors like agriculture and rural enterprises are crucial for maximizing the socio-economic returns of R&D investments in Togo.

3.5.3.3. Dynamic of the physical investment (IP) impact on incomes

Figure 30 presents the impact of increased physical investment (IP) in electricity and gas production and distribution on incomes across different sectors in Togo. Physical investments, such as infrastructure upgrades and capacity expansion, play a critical role in economic development by enhancing productivity, improving energy access, and stimulating economic activities. The income growth for firms and government revenues is relatively consistent but modest, indicating that physical investments contribute to increased industrial output and fiscal revenues. According to Aschauer (1989), public infrastructure investment directly boosts private sector productivity by reducing operational bottlenecks and enhancing the efficiency of production systems. In the case of Togo, improved energy distribution likely supports industrial performance, enabling firms to scale operations and governments to collect more revenues through taxes and reduced energy import costs.

The steady rise in household incomes reflects the indirect benefits of physical investments in the energy sector, such as job creation and higher wages. Physical investment in energy infrastructure reduces operational downtimes and ensures reliable electricity supply, which improves productivity and income generation, as argued by Calderón and Servén (2010). Reliable energy access also supports household businesses and increases disposable incomes for employees. The moderate-income growth in agriculture highlights the limited but notable role of physical energy investments in rural economies. Improved energy access enables mechanization, irrigation, and processing in agriculture, leading to higher productivity and earnings. As Dinkelman (2011) shows, electrification is crucial for unlocking rural economic potential, but its full impact depends on complementary investments in skills and equipment, which might explain the relatively slow growth in this sector.

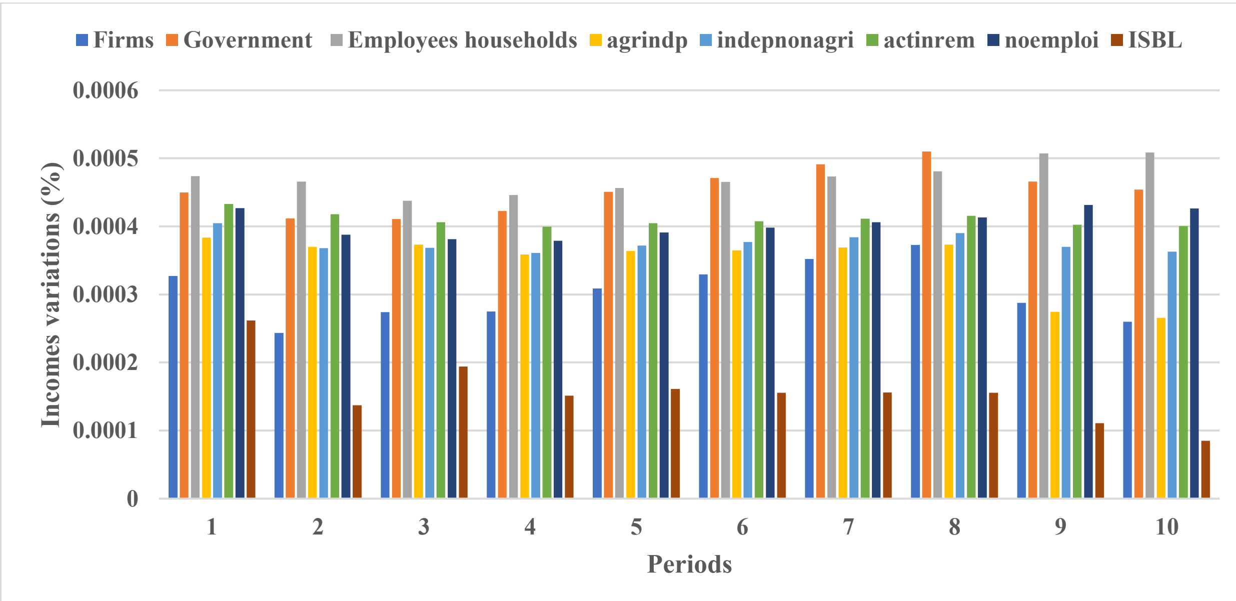

Figure 30: Dynamic of the physical investment (IP) impact on incomes

The stable income growth in this sector reflects the importance of energy reliability for small and medium enterprises (SMEs). Better energy infrastructure reduces production costs and improves business efficiency, as highlighted by Gertler et al. (2016). SMEs, which dominate the informal economy in Togo, benefit significantly from such improvements, driving steady growth in non-agricultural independent production incomes. The slight rise in incomes related to unemployment reflects government efforts to address energy-driven unemployment challenges through social programs. However, as Autor et al. (2020) point out, the transition to more capital-intensive production due to physical investments can lead to labor displacement if not paired with active labor market policies and reskilling initiatives.

Physical investment in electricity and gas production positively impacts incomes across sectors, with notable benefits for firms, government, and employees' households. However, the uneven distribution of gains, particularly in agriculture and ISBL, underscores the need for targeted strategies to maximize benefits. Combining physical investments with policies that promote inclusive development, such as skills training, SME support, and rural electrification programs, can enhance socio-economic outcomes.

3.5.3.4. Dynamic of savings in the base scenario

Figure 31 reflects the dynamic of savings in Togo's base scenario, focusing on different socio-economic groups and sectors over 10 years. Savings are a critical indicator of economic stability, investment potential, and resilience, influencing long-term economic growth and poverty alleviation.

Savings for employees' households steadily increase over the period, reflecting rising disposable incomes. This growth suggests improvements in wage levels or employment opportunities, which are essential for boosting household savings. As Carroll and Weil (1994) highlight, rising incomes positively correlate with higher savings rates, as households have more capacity to save beyond their consumption needs. Additionally, improved energy infrastructure and economic stability may contribute to this upward trend, allowing households to allocate resources more efficiently.

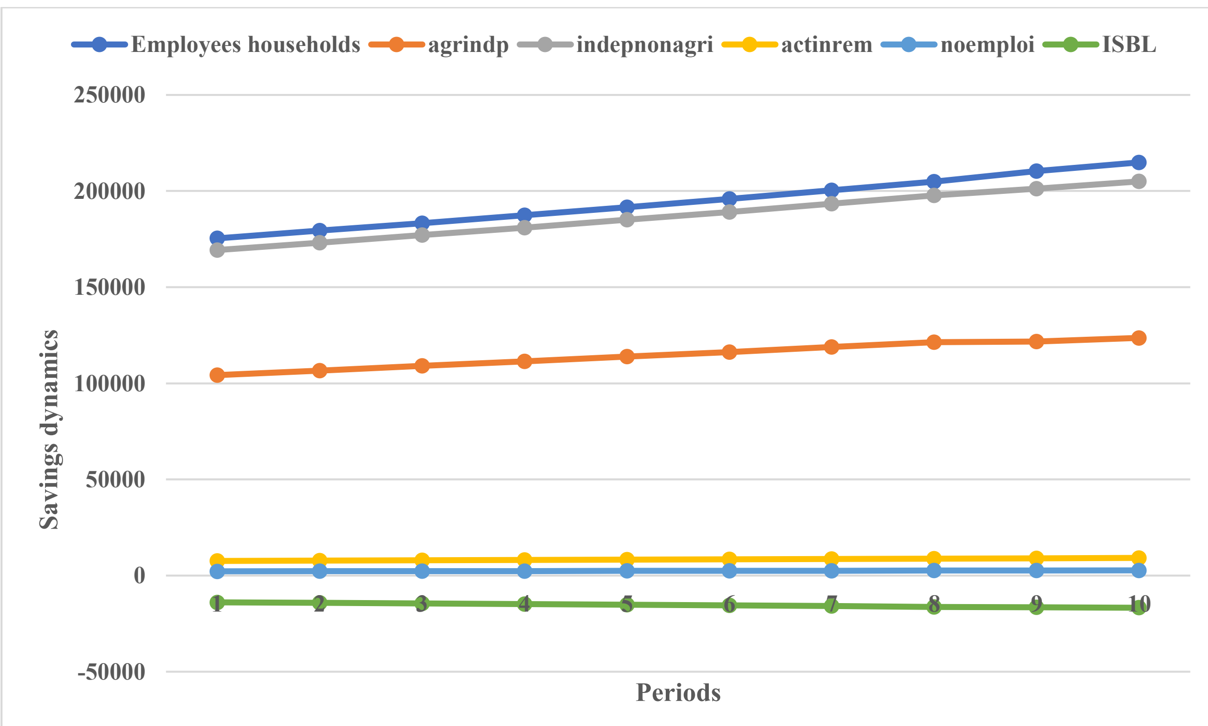

Figure 31: Dynamic of savings in the base scenario

Savings for agricultural producers also grow consistently, though at a slightly slower pace compared to employees' households. This trend may be linked to moderate improvements in agricultural productivity and access to markets. Electrification and infrastructure investment, as argued by Dinkelman (2011), often play a pivotal role in enabling rural producers to increase output and income. However, the slower growth might indicate persistent vulnerabilities in the agricultural sector, such as climate variability and limited access to credit or technology.

Non-Agricultural Independent Producers (indepnonagri) group exhibits robust savings growth, highlighting the economic benefits of increased reliability in electricity and energy services for small businesses and entrepreneurs. According to Gertler et al. (2016), improved access to reliable energy reduces production costs and enhances business profitability, directly contributing to higher savings among non-agricultural producers. The consistent rise underscores the role of SMEs as engines of economic growth and savings accumulation in Togo. Savings for ISBL remain negative throughout the period, highlighting financial challenges faced by non-profit organizations and other institutions that rely on donations, subsidies, or grants. The persistent deficit indicates a reliance on external support, which can be unsustainable without a robust funding strategy. As Bloom et al. (2013) argue, improving infrastructure and institutional efficiency can reduce operational costs and help these organizations better allocate resources.

The overall growth in savings across most sectors suggests a positive economic trajectory, supported by investments in infrastructure and energy. However, disparities in savings dynamics indicate the need for targeted interventions. For instance, rural agricultural producers and unemployed individuals may benefit from policies promoting financial inclusion, access to credit, and skills development. Similarly, addressing the financial deficits of ISBL can enhance their capacity to contribute to social and economic development.

3.5.3.4.1. Dynamic of the energy policies' impact on firms' savings

The dynamic of energy policies' impact on firms' savings reveals critical insights into the effectiveness of investments in Research and Development (R&D), Physical Investment (IP), and their combination in the electricity and gas sectors (**Figure 32**). The data shows that R&D consistently generates the highest impact on firms' savings, highlighting its role in fostering innovation, enhancing efficiency, and reducing long-term costs. Studies by Acemoglu et al. (2012) emphasize that targeted R&D investments can drive productivity gains and economic growth, particularly in the clean energy sector. The diminishing returns in the later years suggest that R&D strategies should evolve to maintain their effectiveness and ensure sustained innovation.

Physical investments, while essential, have a more modest impact on savings due to their capital-intensive nature and longer payback periods. These investments improve infrastructure reliability and capacity, indirectly contributing to cost reductions and operational efficiency. However, their lower immediate impact relative to R&D underscores the need for complementary measures. Hulten and Isaksson (2007) note that the benefits of physical investments are maximized when paired with skilled labor and technological advancements, supporting the notion that infrastructure improvements alone may not yield optimal outcomes.

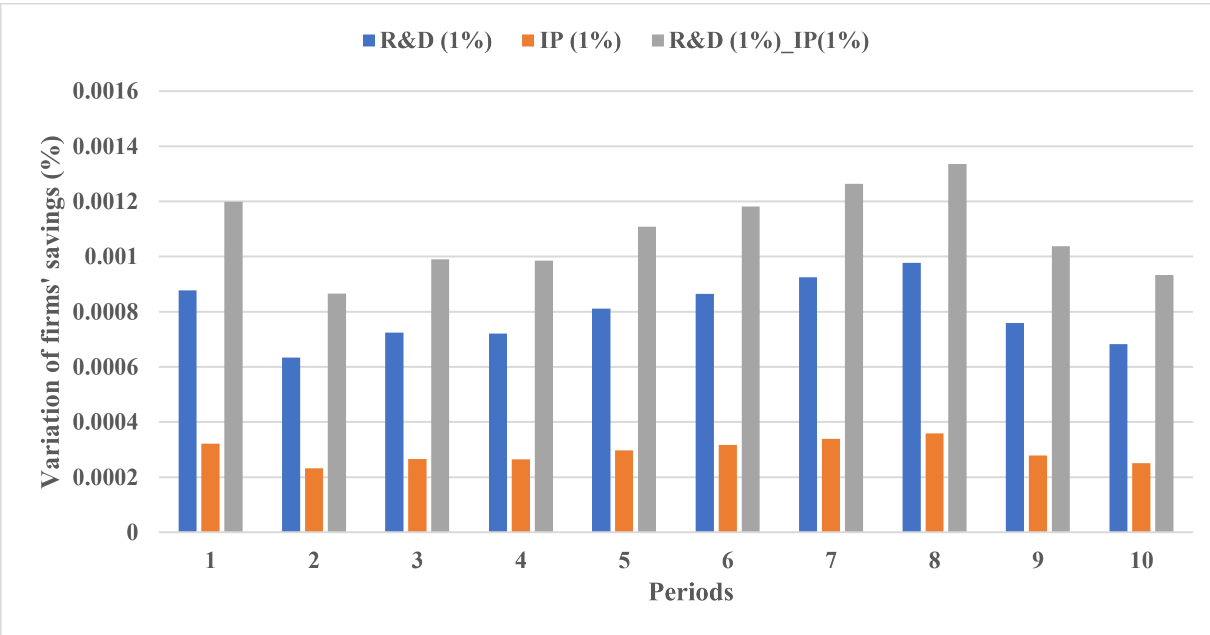

Figure 32: Dynamic of the energy policies' impact on firms' savings

The combination of R&D and IP investments demonstrates a synergistic effect, with firms' savings significantly exceeding the sum of their impacts in most scenarios. This finding highlights the importance of integrated policy approaches, where technological advancements driven by R&D amplify the benefits of infrastructure upgrades. Jaffe et al. (2005) argue that such combined strategies are crucial for achieving efficiency and economic gains in the energy sector. The peak impact observed in mid-periods suggests an optimal timeline for implementing these strategies, balancing immediate benefits with long-term sustainability.

3.5.3.4.2. Dynamic of the energy policies' impact on households' savings

Figure 33 indicates that R&D consistently produces the most substantial impact on households' savings, underscoring its critical role in improving energy efficiency, reducing costs, and fostering technological innovations. Studies by Popp (2002) highlight that energy-related R&D investments lead to technological advancements that reduce energy costs for households, thus directly increasing disposable income and savings.

In contrast, physical investments yield relatively modest impacts on households' savings. While infrastructure upgrades in the energy sector enhance reliability and accessibility, their direct financial benefits to households are less pronounced. However, they play an essential role in supporting broader economic stability and ensuring the smooth delivery of energy services. According to Stern (2006), physical investments are foundational for enabling long-term efficiency gains, especially when complemented by innovations from R&D efforts.

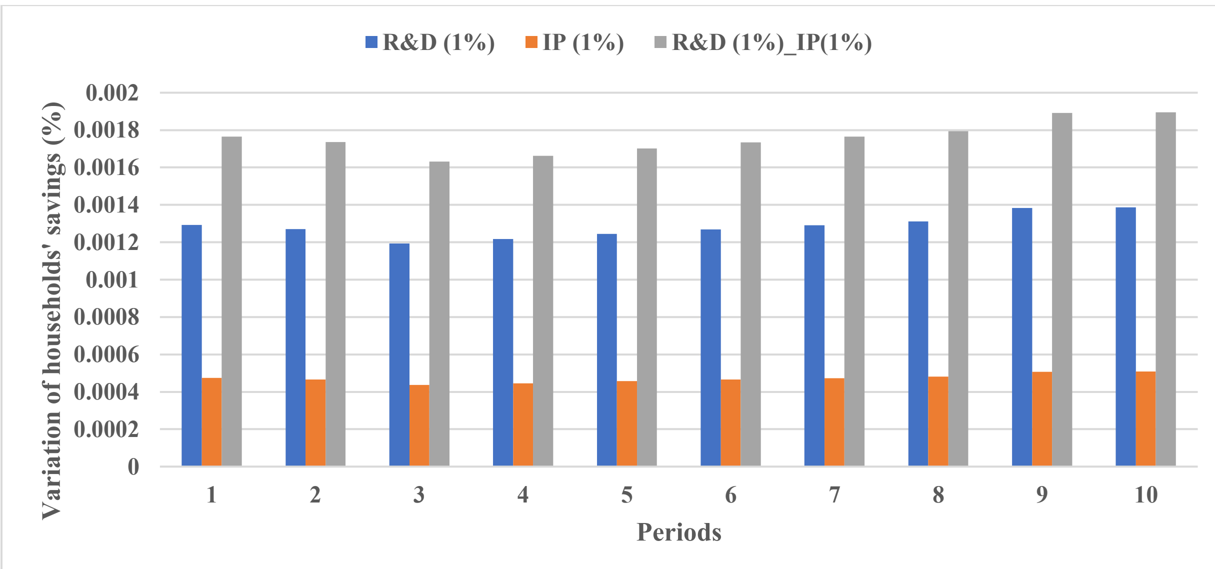

Figure 33: Dynamic of the energy policies' impact on households' savings

The combined investment in R&D and IP demonstrates a synergistic effect, significantly amplifying the impact on households' savings compared to the effects of either investment alone. The data consistently shows higher savings under the combined scenario, with the peak effects observed in later years, suggesting the long-term benefits of integrated policy approaches. This supports the findings of Dechezleprêtre et al. (2011), who emphasize that combining innovation with infrastructure improvements maximizes cost reductions for end-users and drives economic welfare.

Over time, households' savings exhibit an upward trajectory under all scenarios, reflecting the cumulative benefits of sustained investments in energy policies. The higher savings from R&D and IP combination highlight the importance of a dual strategy, where innovations from R&D complement the structural enhancements provided by physical investments. This alignment with the literature underscores the importance of balanced energy policy approaches that address both the immediate and long-term needs of households.

3.5.3.4.3. Dynamic of the energy policies' impact on the government's savings

Figure 34 reveals that R&D consistently yields the highest returns on government savings compared to IP alone. This result underscores the role of R&D in fostering innovation, enhancing energy efficiency, and reducing operational costs, which collectively increase government fiscal surpluses. Popp (2002) and Jaffe et al. (2005) have argued that energy-related R&D investments stimulate cost-effective technologies that reduce expenditures in public energy projects, enabling governments to allocate resources more efficiently.

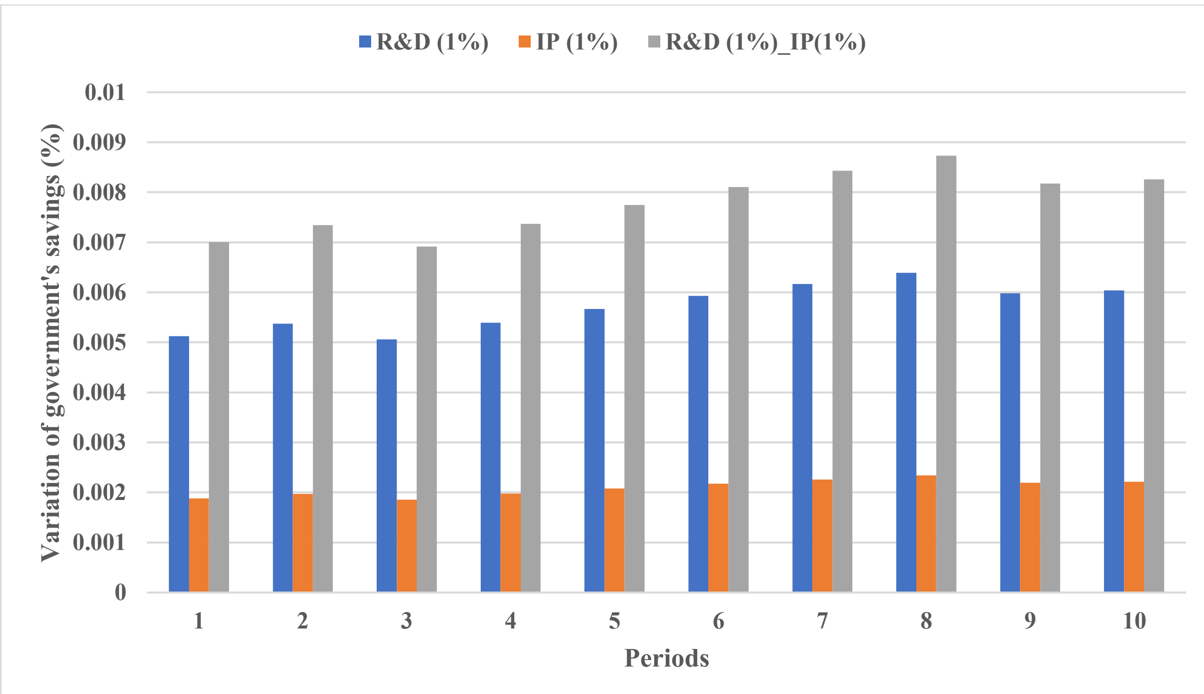

Figure 34: Dynamic of the energy policies' impact on the government's savings

Physical investments in the energy sector also contribute positively to government savings, though to a lesser extent than R&D. Infrastructure development in energy distribution systems ensures reliability and scalability, supporting economic growth and increasing tax revenues indirectly. However, its immediate impact on government savings is moderated by the significant upfront costs associated with physical infrastructure. Stern (2006) emphasizes that while physical investments are indispensable, their returns are often long-term and dependent on concurrent technological advancements.

The combined R&D and IP investment scenario shows a synergistic effect, producing consistently higher government savings than either strategy alone. This synergy is particularly evident in later years, reflecting the compounding benefits of integrating innovation with robust infrastructure development. The findings align with Dechezleprêtre et al. (2011), who observed that joint approaches leveraging R&D and physical investments maximize efficiency gains, reduce system costs, and enhance fiscal outcomes.

Notably, the savings from R&D and combined investments demonstrate a more consistent growth trend, whereas IP savings show relatively smaller increments. This suggests that governments should prioritize R&D as a strategic tool for achieving sustainable fiscal benefits while maintaining balanced investments in physical infrastructure to ensure a holistic energy policy.

3.5.4. Impact on Gross Domestic Product

3.5.4.1. Dynamic of GDP in the base scenario

The dynamics of Gross Domestic Product (GDP) in the base scenario reveal a consistent upward trajectory across all measures, reflecting steady economic growth. GDP at basic prices, purchasers' prices from the perspective of final demand, and market prices exhibit synchronized trends, with gradual annual increases over the ten years. This growth underscores the resilience and positive momentum of the economy, supported by structural factors such as investment, consumption, and production efficiencies.

The GDP at basic prices, which excludes taxes and subsidies, serves as a measure of production efficiency. Its steady growth indicates enhanced productivity in core sectors, likely driven by improvements in technology, labor efficiency, and resource allocation. The increase aligns with studies by Barro (1996), which emphasize the role of technological advancements and institutional quality in sustaining production growth. GDP at purchasers' prices, representing the final demand perspective, illustrates the robust demand for goods and services in the economy. The alignment of this measure with market prices reflects a balanced interplay between production and consumption, supported by favorable economic policies and household income growth. This is consistent with Keynesian economic principles, which suggest that demand-side factors play a critical role in driving GDP growth (Blanchard & Johnson, 2013).

The GDP at market prices, measured both from income and market perspectives, highlights the comprehensive nature of growth, factoring in taxation and subsidies. The steady growth pattern indicates effective fiscal management and the ability of the economy to generate and redistribute income equitably. As observed by Aghion and Howitt (2009), economies with stable fiscal policies and investments in innovation tend to experience sustained GDP growth.

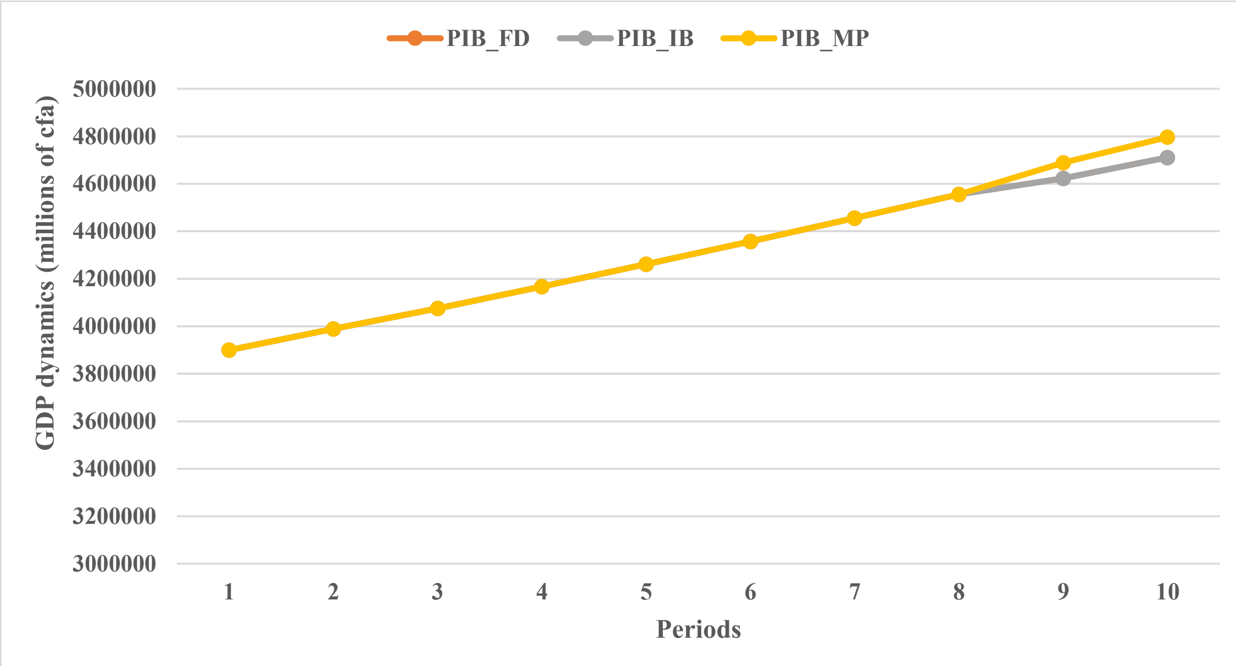

Figure 35: Dynamic of GDP in the base scenario

A notable observation is the marginally higher figures in the final years under the market price perspective. This discrepancy suggests an increase in government intervention, potentially through subsidies or investments in public goods, which contribute to economic welfare and further stimulate GDP. This aligns with findings by Acemoglu et al. (2014), who argue that state-led investments in infrastructure and human capital can have long-term positive effects on economic growth.

3.5.4.2. Dynamic of the energy policies' impact on GDP variation

The dynamics of GDP variation in response to increased investment in research and development (R&D) and physical investment (IP) for electricity and gas production and distribution reveal important insights about the impact of energy policies on economic performance (**Figure 36**). The results show that even a small increase in investment (1%) leads to positive changes in GDP variation across scenarios. When both R&D and IP investments are combined, the variations are consistently higher compared to standalone investments, indicating synergistic effects between technological advancements and infrastructure development.

The impact of 5% and 10% combined R&D and IP investments on GDP variation is particularly pronounced, with steady increases in percentage changes over time. This significant growth underscores the transformative potential of scaling up energy investments, especially in sectors crucial for economic productivity. These findings align with research by Aghion et al. (2005), which demonstrates that sustained innovation-driven investments lead to higher GDP growth rates through productivity improvements and technological spillovers.

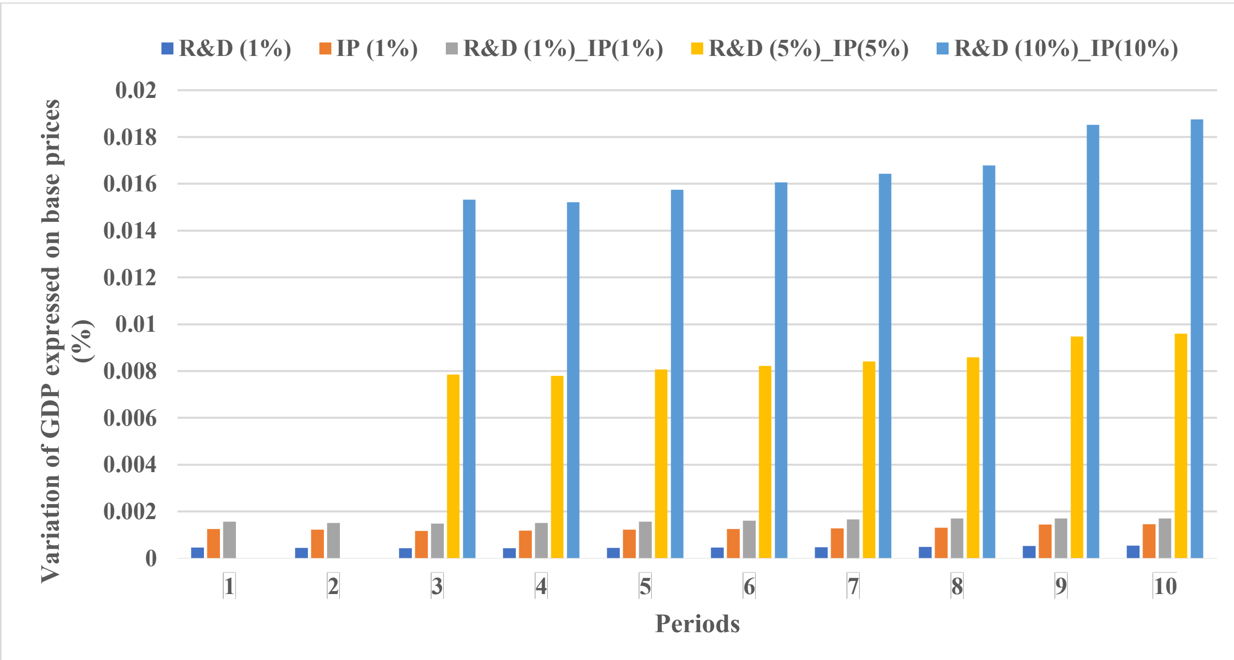

Figure 36: Dynamic of the energy policies' impact on GDP variation

The results for standalone R&D investments exhibit relatively smaller but consistent positive effects on GDP variation. This suggests that while R&D enhances technological capabilities and long-term economic growth, its immediate impact on GDP may be moderated by the time needed for innovations to diffuse across industries. This observation is consistent with Romer (1990), who emphasizes the role of R&D in fostering endogenous growth through knowledge accumulation.

On the other hand, IP investments generate relatively higher GDP variations in the short term, indicating their direct and immediate impact on economic activity. Physical investments in energy infrastructure contribute to job creation, enhanced energy availability, and improved industrial efficiency, as noted by Lin and Rosenblatt (2012). These effects are critical in energy-dependent economies, where infrastructure development underpins broader economic growth.

The combination of R&D and IP investments amplifies GDP variation, highlighting the importance of integrated energy policies. This synergy is evident as technological advancements from R&D improve the efficiency and output of infrastructure investments. The results also suggest that the returns on combined investments are nonlinear, with higher percentages (e.g., 10%) yielding disproportionate benefits compared to lower investment levels. This is consistent with Jones and Williams (1998), who argue that the social returns on R&D and infrastructure investment often exceed private returns, necessitating coordinated public and private efforts.

3.5.5. Sensitivity analysis: Walras law verification

Walras' Law is a cornerstone of general equilibrium theory, asserting that if all but one market in an economy is in equilibrium, then the remaining market must also be in equilibrium. This principle is vital for ensuring internal consistency in Computable General Equilibrium (CGE) models. Its verification serves both theoretical and practical purposes, particularly when applied to policy analysis and economic forecasting. The primary objective of verifying Walras' Law in a CGE model is to ensure the model's structural and mathematical consistency. Since CGE models are based on the neoclassical framework where markets for goods, factors, and financial assets interact, the following objectives are central:

- Model integrity: Verifying Walras' Law ensures that the model adheres to the principle of budget constraints, where aggregate demand equals aggregate supply in equilibrium. This consistency builds confidence in the model's outcomes (Arrow & Debreu, 1954).
- Error detection: A failure to satisfy Walras' Law might indicate numerical inaccuracies, parameter mis-specifications, or coding errors within the CGE model, necessitating troubleshooting (Shoven & Whalley, 1992).
- Policy validity: Ensuring compliance with Walras' Law strengthens the reliability of simulated policy shocks, as deviations could result in misleading conclusions (Ginsburgh & Keyzer, 1997).

In different scenarios, results in the Walras Law show zero coefficients over the years. This describes a situation where the excess demand or supply in one market is intentionally or numerically set to zero. Walras' Law reinforces the closure of the system, meaning the economy's equations are balanced without over- or under-specification (Löfgren et al., 2002). This stability is crucial for solving the nonlinear equations inherent in CGE models. Because of Walras' Law, one of the equilibrium conditions becomes redundant. This feature simplifies the system without compromising its completeness, reducing computational complexity (Devarajan et al., 1997). The model used for policy analysis ensures that all simulated outcomes, including changes in welfare, sectoral outputs, and prices, are consistent across markets (Hertel, 1997). In practical applications, the satisfaction of Walras' Law serves as a validation mechanism for ensuring that the model faithfully represents the theoretical framework on which it is based (Dixon & Parmenter, 1996).

Conclusion and policy implications

Togo's energy policies, focused on investments in research and development (R&D) and physical infrastructure, demonstrate a profound potential to transform its economy, fostering sustainable development, economic growth, and resilience against climate and economic shocks. This chapter explores the dynamic impacts of energy policies, specifically R&D and physical investments in electricity and gas production, on Togo's economy using a computable general equilibrium model. It reveals how energy investments significantly enhance economic growth, productivity, and environmental sustainability while addressing structural challenges.

The results reveal that R&D consistently generates the most substantial benefits across multiple dimensions (firms, households, and government savings) while physical investments provide the necessary infrastructure foundation. The combined investments amplify these impacts, highlighting the synergistic relationship between innovation and infrastructure. R&D investments emerge as the most efficient in driving long-term economic benefits by fostering innovation, enhancing energy efficiency, and reducing costs. This aligns with global findings emphasizing the transformative impact of R&D on productivity and growth (Popp, 2002; Acemoglu et al., 2012). However, their short-term impacts may be moderated by implementation lags, suggesting the need for sustained support and a focus on complementary measures like skills development and knowledge transfer. Physical investments, while offering more immediate economic stimulation, need to be strategically aligned with technological advancements to maximize their effectiveness and returns.

The dynamic analysis of energy policies through simulation scenarios demonstrates that higher levels of combined R&D and IP investments yield disproportionately higher benefits, particularly under the 10% investment scenario. These findings are consistent with literature advocating for aggressive and coordinated energy policies to meet sustainability goals (Dechezleprêtre et al., 2011; Stern, 2006). While incremental investments offer positive impacts, substantial and integrated approaches are necessary for transformative growth. The sectoral analysis underscores the uneven distribution of benefits, with agricultural and informal sectors growing more modestly compared to industrial and formal sectors. This indicates the need for targeted policies to address structural barriers, enhance rural electrification, and support small enterprises. Policies promoting financial inclusion, access to credit, and tailored energy solutions for underserved regions are critical for ensuring equitable impacts.

The government's role is crucial in scaling these investments, creating an enabling environment for private sector participation, and ensuring fiscal sustainability. Given the synergistic effects observed, energy policies should integrate incentives for innovation with infrastructure development to attract private investments and international collaboration. The findings also emphasize the importance of addressing transitional costs, regulatory bottlenecks, and adaptation challenges to maximize the socio-economic returns on energy investments.

Policymakers should adopt integrated energy strategies that balance investments in research and development (R&D) with physical infrastructure expansion to maximize the complementary benefits of these approaches. By fostering innovation and enhancing energy infrastructure reliability, such policies can drive sustained economic growth and productivity. It is crucial to implement sector-specific measures that target underperforming areas such as agriculture and rural enterprises, ensuring that the benefits of energy investments are equitably distributed across the economy. Scaling up energy-related R&D and physical investments to at least 5–10% of GDP will accelerate technological advancements and expand infrastructure capacity, aligning Togo with global energy transition goals. To support these efforts, regulatory frameworks, and fiscal incentives should be established to attract private sector participation, enabling a more dynamic and resource-efficient energy sector. Additionally, strengthening institutional capacity and governance frameworks is essential to enhance the efficiency and socio-economic impacts of energy investments, ensuring that these strategies contribute to both immediate and long-term development objectives.

GENERAL CONCLUSION AND POLICY IMPLICATIONS

This dissertation presents an extensive analysis of the interplay between renewable energy adoption, energy efficiency, and economic development within the ECOWAS region, with a specific focus on Togo. Through a combination of dynamic modeling, empirical analysis, and case studies, this research highlights the critical role of renewable energy (RE) and energy efficiency (EE) in enhancing energy security (ES), fostering economic growth, and mitigating the impacts of climate change. The study offers insights into how energy policies, R&D investments, and targeted interventions at both national and regional levels can drive significant progress towards achieving sustainability goals, improving energy access, and fostering socio-economic development.

The growing consumption of renewable energy positively impacts energy security (ES) and energy efficiency (EE) in the long term, with hydropower, solar photovoltaic, and biogas emerging as the most impactful sources. Energy efficiency is particularly high in Cabo Verde, which has effectively dealt with inflation, human capital quality, and institutional quality. However, Togo lags, requiring a focus on integrating energy efficiency into educational and investment policies. These findings highlight the importance of renewable energy adoption for improving energy security and efficiency in the ECOWAS region.

At the residential level, renewable energy adoption enhances households' propensity to invest in energy efficiency, with factors such as household characteristics, environmental attitudes, and living conditions influencing adoption decisions. Investments in renewable energy are linked to both monetary and non-monetary energy efficiency investments. Furthermore, subjective life satisfaction and household type (e.g., house vs. flat) are significant determinants of renewable energy adoption. Households that invest in renewable energy are more likely to reduce their energy demand and carbon footprint. This synergy between RE adoption and energy efficiency investment offers a pathway toward sustainable energy usage at the household level.

Togo's energy policies, focusing on research and development (R&D) and physical infrastructure investments, have significant potential for promoting sustainable economic growth and resilience. R&D investments drive long-term economic benefits, fostering innovation, reducing costs, and enhancing energy efficiency. Meanwhile, physical infrastructure investments provide the necessary foundation for energy sector development. A coordinated approach, combining both types of investments, generates more substantial benefits, particularly in terms of job creation, technological advancement, and addressing rural electrification challenges.

- **For ECOWAS countries:**
- **Promote renewable energy adoptio**n: To accelerate energy security and efficiency, ECOWAS countries must prioritize renewable energy sources such as hydropower, solar photovoltaic (PV), and biogas. These sources not only contribute to long-term sustainability but also help reduce dependence on fossil fuels. Governments should enact targeted policies and financial incentives, such as tax credits, subsidies, and soft loans, to encourage investments in renewable energy infrastructure. Regulatory frameworks should be streamlined to reduce administrative burdens and attract private-sector investment. Additionally, regional cooperation among ECOWAS nations should be fostered to enhance cross-border energy exchange and share best practices for renewable energy development.
- **Invest in energy efficiency programs**: Energy efficiency is key to reducing overall energy consumption and mitigating environmental impacts. Policymakers should implement comprehensive programs that promote energy-efficient technologies, focusing on residential, commercial, and industrial sectors. These initiatives could include offering subsidies for energy-efficient appliances, setting minimum standards for building insulation, and providing financial incentives for companies investing in energy-efficient technologies. Furthermore, governments should encourage the adoption of energy-saving practices through awareness campaigns, educating the public on the benefits of reducing energy consumption both for economic and environmental reasons.
- **Implement country-specific policies**: While ECOWAS countries share common goals related to energy security and efficiency, each nation faces unique challenges due to varying economic structures, energy needs, and resource availability. Policymakers should design energy policies that are tailored to the specific circumstances of each country. For example, Cabo Verde's successful energy efficiency strategies could serve as a model for other nations, highlighting the importance of institutional quality, human capital, and inflation control. In contrast, countries like Togo should focus on integrating energy efficiency into education systems, building local capacity, and ensuring both monetary and non-monetary investments in clean energy technologies. Policies should be flexible to account for each country's unique resources and socio-economic conditions, promoting equitable development across the region.

- **For Togo:**

✓ **Foster renewable energy adoption at the household level:** For renewable energy adoption to become widespread, Togo must implement policies that encourage households to invest in clean energy systems. This includes addressing affordability concerns by providing financial incentives such as grants, subsidies, and low-interest loans. Additionally, government-sponsored public education campaigns can raise awareness about the long-term environmental and economic benefits of adopting renewable energy, particularly solar PV and biogas. Household-level adoption of renewable energy can significantly reduce energy costs, enhance energy security, and mitigate the impacts of climate change.

✓ **Enhance synergies between renewable energy and energy efficiency**: Togo should design policies that encourage a holistic approach to energy sustainability by integrating renewable energy adoption with energy efficiency measures. Incentives should be introduced to encourage households and businesses to invest in both renewable energy technologies and energy-efficient appliances. For instance, the government can offer rebates or tax credits for households that install solar panels alongside energy-efficient lighting or insulation. This synergy will not only reduce overall energy consumption but also lower carbon emissions and create a more resilient energy system. Educating the public on the benefits of this dual approach is crucial to ensuring the success of such policies.

✓ **Invest in energy efficiency and infrastructure**: To support the transition to renewable energy, Togo must prioritize investments in energy infrastructure, particularly in rural areas where access to electricity is limited. Developing energy-efficient buildings, expanding access to clean energy technologies, and promoting rural electrification should be central goals of Togo's energy policy. Infrastructure development should be aligned with renewable energy integration, ensuring that the grid can accommodate decentralized renewable energy sources like solar and wind power. Additionally, investment in energy efficiency should focus on both residential and industrial sectors, encouraging industries to adopt energy-efficient technologies to reduce production costs and minimize their environmental impact.

✓ **Support research and development investment in the energy sector**: A robust research and development (R&D) strategy is crucial for fostering innovation in the energy sector. Togo should prioritize R&D investments to develop locally appropriate renewable energy technologies and energy efficiency solutions. Government funding, partnerships with universities, and collaboration with international research institutions can accelerate the development and commercialization of clean energy technologies. The government should create incentives for private companies to invest in R&D, particularly for off-grid and rural energy solutions that are tailored to the specific needs of Togo's population.

✓ **Encourage private sector participation**: Encouraging private sector participation in the renewable energy and energy efficiency sectors is vital for scaling up investments. Togo should create a favorable regulatory environment that promotes private investments in energy projects, such as offering tax breaks, financial incentives, and favorable loan terms for businesses involved in renewable energy production and energy efficiency improvements. Public-private partnerships (PPPs) can play a significant role in financing and implementing large-scale renewable energy infrastructure projects. Moreover, improving access to credit for small and medium-sized enterprises (SMEs) will enable them to adopt renewable energy solutions and improve energy efficiency.

- **Long-term vision for Togo's energy sector:**

✓ Togo's long-term energy strategy should aim at achieving sustainable development through the adoption of a diversified energy mix that includes significant investments in renewable energy sources, energy efficiency, and infrastructure development. The goal is to reduce the country’s dependence on fossil fuels, improve energy security, and contribute to global climate change mitigation efforts. By prioritizing renewable energy and energy efficiency, Togo can enhance its energy resilience, promote economic growth, and create new job opportunities in the clean energy sector.

✓ Togo should strive to reach net-zero emissions by the middle of the century, with the active integration of clean energy solutions across all sectors, residential, industrial, and agriculture. Developing decentralized energy systems, such as off-grid solar and biogas systems, will be crucial for providing affordable and reliable energy to rural areas. In parallel, Togo must focus on creating the regulatory frameworks and financial mechanisms necessary to attract both local and international investments in the energy sector.

✓ The country should work toward enhancing regional collaboration with neighboring ECOWAS states to promote cross-border energy trade, share best practices, and create joint infrastructure projects. Ultimately, a balanced approach that integrates renewable energy adoption, energy efficiency, and infrastructure expansion will ensure that Togo's energy sector contributes significantly to its broader sustainable development goals.

The implementation of effective energy policies in ECOWAS countries and Togo requires a multi-faceted approach. First, governments must introduce clear and consistent policies, tax incentives, and regulations that support renewable energy projects and energy efficiency programs. A robust and enabling legal framework will provide the necessary support for both local and international investors, creating a conducive environment for renewable energy growth. In parallel, public awareness campaigns are crucial for educating households, businesses, and policymakers on the benefits of renewable energy adoption and energy efficiency investments. These campaigns should highlight long-term cost savings, environmental benefits, and the role of clean energy in national energy security, making the case for a transition to more sustainable energy systems. Furthermore, regional collaboration and knowledge sharing will play a vital role in accelerating energy transitions. ECOWAS member states should work together to create platforms for exchanging best practices and implementing joint projects. This regional cooperation will help improve energy infrastructure, enhance cross-border energy trade, and ultimately contribute to greater energy security across the region. Additionally, private sector engagement is essential for scaling up renewable energy adoption and energy efficiency investments. Public-private partnerships (PPPs) should be encouraged through the creation of financial mechanisms, such as low-interest loans or guarantees, that mitigate risks for private investors. These mechanisms will provide the financial support needed for the rapid deployment of clean energy technologies and infrastructure development. Overall, successful implementation of these strategies requires strong political commitment, sustained investment, and collaboration across all levels of government, industry, and civil society. By combining policy support, public awareness, regional cooperation, and private sector involvement, ECOWAS countries and Togo can build a more resilient, sustainable, and inclusive energy future.

In conclusion, this research highlights the critical role of renewable energy adoption, energy efficiency investments, and targeted energy policies in promoting sustainable energy security and economic growth in Togo and the broader ECOWAS region. By adopting integrated strategies that consider country-specific conditions and fostering synergies between energy efficiency and renewable energy adoption, these nations can ensure a sustainable energy future. Continued investments in both R&D and physical infrastructure are essential to driving long-term economic benefits and achieving global sustainability goals. Further research should focus on the long-term impacts of renewable energy and energy efficiency investments on economic development, poverty reduction, and social well-being. Additionally, exploring the role of new and emerging technologies, such as smart grids and energy storage systems, in enhancing the effectiveness of renewable energy systems will be critical for advancing energy sustainability. Finally, investigating the behavioral aspects of energy consumption, including the role of social norms, attitudes, and perceptions, can provide deeper insights into how households and businesses make energy-related decisions.

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APPENDIX

Enquête sur l'adoption des énergies renouvelables et l'investissement en efficience énergétique au Togo

Ce questionnaire développé rentre dans le cadre de notre travail de recherche dont le thème est : l'impact de la perception environnementale des ménages sur l'investissement dans l'efficacité énergétique et l'adoption des énergies renouvelables au Togo.

Le présent questionnaire nous permettra :

- D'analyser les facteurs explicatifs de la perception environnementale des ménages au Togo
- Capter l'impact de cette perception sur l'investissement dans l'efficacité énergétique
- Capter l'impact de cette perception sur l'adoption des énergies renouvelables au Togo
- Et enfin, analyser le rôle de cette perception dans l'interaction entre l'investissement dans l'efficacité énergétique et l'adoption des énergies renouvelables au Togo.

Merci de bien vouloir prendre part à cet exercice de collecte de données en répondant à ces quelques questions relatives au changement climatique et à l'accès, l'utilisation des services énergétiques dans votre localité.

Partie 0 : Identification

Partie A : Caractéristiques démographiques

Partie B : Attitudes personnelles

Partie C : Energie

Partie D : Politique d'atténuations du changement climatique et de promotion des énergies renouvelables

Partie 0 : Identification

00 : Localisation géographique	1. Latitude 2. Longitude	03 : Canton	-----------
01 : Région	-------------	03 : Village	------------
02 : Préfecture	-------------	04 : Zone	1. Urbain 2. Rural
Quartier	Date de l'enquête	../../2023	Heure :

Partie A : Caractéristiques démographiques

A1 : Combien de personnes (vous y	/------/

compris) vivent dans votre foyer ?	
A2 : Combien d'enfants (de moins de 18 ans) vivent dans votre foyer ?	/------/
A3 : Parmi ces enfants, combien ont moins de 5 ans ?	/------/
A4 : Etes-vous le chef du ménage ?	**1.** Oui 2. Non
A5 : Si Non qui est le chef de votre ménage ?	-----------------------------
A6 : Sexe du chef ?	1. Masculin 2. Féminin
A7 : Age du chef ?	/------/
A8 : Quelle est la situation matrimoniale du chef de ménage ?	1.Célibataire 2.Marié(e) monogame 3.Marié(e) polygame 4.Union libre 5.Veuf(ve) 6.Divorcé(e) 7.Séparé(e)
A8 : Quel niveau d'étude identifie le mieux le chef ?	1. Aucun niveau 2. CP1 3. CP2 4. CE1 5. CE2 6. CM1 7. CM2 8. 6ème 9. 5ème 10. 4ème 11. 3ème 12. Seconde 13. Première 14. Terminale 15. Universitaire 16. Professionnelle 17. Alphabétisation
A9 : Quelle est sa situation professionnelle actuelle du chef de ménage ?	1. A votre compte 2. Salarié(e) (à temps plein, à temps partiel ou en congé temporaire) 3. Retraité(e) 4. Homme/femme au foyer 5. En recherche d'emploi/sans emploi 6. Etudiant(e) 7. Dans l'impossibilité de travailler, par exemple en invalidité 8. Autre, veuillez préciser

A10 : Dans quelle branche d'activité le chef du ménage a-t-il travaillé ou travaille-il principalement ?	1. Sans emploi 2. Agriculture, Elevage, Pêche… 3. Mines, carrières 4. Industries, électricité, eau	5. Construction 6. Commerce 7. Transport 8. Restauration, hôtel 9. Arts et spectacles 10. Services 11. NSP
A11 : Etes-vous (et/ou un autre membre de votre foyer) propriétaire(s) de votre résidence principale actuelle	1. Oui 2. Non	
A12 : Caractéristiques de la résidence principale	1. Un appartement 2. Une maison 3. Une chambre WC/Douche interne 4. Une chambre simple 5. Autre, ……… ./	
A13 : Surface approximative de votre résidence principale	A13_1 : Unité	A13_2 : Estimation
A14 : Depuis combien de temps environ habitez-vous dans cette résidence principale	1. Moins de 2 ans 2. 2 à 5 ans 3. 6 à 15 ans 4. Plus de 15 ans	

Partie B : Attitudes personnelles

B1 : Dans quelle mesure êtes-vous satisfait(e) de votre vie actuelle ?	1. Très satisfait 2. Satisfait 3. Moyennement satisfait 4. Non satisfait
B2 : A votre avis, quels sont les problèmes les plus sérieux auxquels le pays doit faire face aujourd'hui ?	1. Tensions et problème sécuritaires (terrorisme, crime, vol) 2. Problèmes économiques (chômage, inflation) 3. Problèmes environnementaux (pollution, déchets, changement climatique) 4. Problèmes de santé (cancer, Covid19)

	5. Problèmes sociaux (pauvreté, discrimination) 6. Autre ………../
B3 : Quelle est l'importance des problèmes environnementaux suivant auxquels le pays fait face ?	1. Pas du tout sérieux 2. Faiblement sérieux 3. Moyennement sérieux 4. Sérieux 5. Très sérieux 6. Extrêmement sérieux 7. Ne sait/sans opinion
B3Q1 : Production des déchets	/-----/
B3Q2 : Pollution atmosphérique	/-----/
B3Q3 : Changement climatique	/-----/
B3Q4 : Pollution de l'eau	/-----/
B3Q5 : Manque de ressources naturelles (forêts, eau, énergie)	/-----/
B3Q6 : Espèces et biodiversité menacées	/------/
B4 : Quel est votre agréement par rapport à chacun des énoncés suivants ?	1. Pas du tout d'accord 2. Pas d'accord 3. D'accord 4. Tout à fait d'accord 5. San opinion
B4Q1 : Je ne suis pas prêt(e) à agir pour l'environnement si les autres n'en font pas de même	/-----/
B4Q2 : Les conséquences environnementales sont souvent exagérées	/-----/
B4Q3 : Les problèmes environnementaux devraient être traités par les générations futures	/-----/
B4Q4 : Les problèmes environnementaux seront résolus de toute façon par les progrès technologiques	/-----/
B4Q5 : Les problèmes environnementaux ne sont qu'une punition des dieux pour le l'humanité	/-----/
B5 : Quelle est votre niveau de satisfaction des aspects suivant de votre environnement local ?	1. Très insatisfait 2. Insatisfait 3. Satisfait 4. Très satisfait 5. Sans opinion
B5Q1 : Qualité de l'air	/-----/
B5Q2 : Qualité de l'eau	/-----/
B5Q3 : Niveau sonore	/-----/

B5Q4 : Ordures	/-----/
B5Q5 : Accès aux espaces verts	/-----/
B6 : Pour chacun des énoncés ci-dessous, cochez la case qui se rapproche le plus de ce que vous pensez de sa pertinence	1. Probablement vrai 2. Certainement vrai 3. Probablement pas vrai 4. Certainement pas vrai 5. Ne sait pas
B6Q1 : Le changement climatique est causé par un trou dans l'atmosphère	/-----/
B6Q2 : Nous contribuons au changement climatique à chaque fois que nous utilisons du charbon, du bois, du pétrole ou de l'essence	/-----/
B6Q3 : Le changement climatique est un phénomène naturel	/-----/

Partie C : Energie

C1 : Dans votre foyer, payez-vous votre électricité en fonction de la quantité d'électricité que vous utilisez ?	1. Oui 2. Non 3. Ne sait pas
C2 : Quel était environ le coût mensuel (maximal, minimal et moyen) de votre consommation d'électricité pour votre résidence l'année dernière ?	
C2Q1 : Cout maximal mensuel	……………..FCFA
C2Q2 : Cout minimal mensuel	……………..FCFA
C2Q3 : Cout moyen mensuel	……………..FCFA
C3: Quelles sources d'énergie utilisez-vous dans le ménage ?	1. Réseau électrique 2. Mini-réseau local 3. Installation solaire individuelle 4. Batterie rechargeable 5. Pile non rechargeable 6. Groupe électrogène 7. Lampe à pétrole 8. Bois/Charbon 9. Gaz 10. Autre……………………
C4 : Pour l'éclairage et climatisation de la maison lesquelles de ces sources sont utilisées ?	1. Réseau électrique 2. Mini-réseau local 3. Installation solaire individuelle 4. Batterie rechargeable 5. Pile non rechargeable 6. Groupe électrogène 7. Lampe à pétrole 8. Bois/Charbon 9. Gaz

	10. Autre……………………
C5 : Pourquoi utilisez-vous ces sources d'énergies ?	1-Disponible 2-Moins chère 3-Facile d'approvisionnement 4-protection de l'environnement 5-Autre (a preciser)……………………..
C6 : Si un tarif énergie renouvelable/verte était disponible sans coût supplémentaire, seriez-vous prêt(e) à l'utiliser ?	1. Oui 2. Non
C7 : Quel pourcentage d'augmentation maximal sur vos coûts annuels êtes-vous prêt(e) à payer pour utiliser uniquement de l'énergie renouvelable ?	---------------%
C8 : Pourquoi ne seriez-vous pas prêt(e) à payer davantage pour utiliser uniquement de l'énergie renouvelable	1. Pas du tout d'accord 2. Pas d'accord 3. D'accord 4. Tout à fait d'accord 5. Sans opinion
C8Q1: Si j'avais plus d'argent, je paierais plus cher pour utiliser uniquement de l'énergie renouvelable	/-----/
C8Q2: Je considère qu'il y a déjà assez d'énergie renouvelable dans l'approvisionnement en électricité au pays	/-----/
C8Q3: Je ne pense pas que payer davantage pour de l'énergie renouvelable fera vraiment augmenter la part des énergies renouvelables dans l'approvisionnement en énergie	/-----/
C8Q4: Je ne pense pas qu'il existe des avantages environnementaux associés aux énergies renouvelables	/-----/
C8Q5: Les énergies renouvelables ne m'intéressent pas	/-----/
C8Q6: Je ne pense pas que je devrais payer plus cher	/-----/
C9: Avez-vous tenu compte des coûts énergétiques au moment d'acheter/construire ou de louer votre résidence principale actuelle	1. Oui 2. Non 3. Pas sûr(e)
C10: Combien, de chacun des appareil électroménagers suivants, possédez-vous chez vous ?	
C10Q1: Réfrigérateurs ou combinés réfrigérateur/congélateur	/-----/
C10Q2: Congélateur indépendant	/-----/
C10Q3: Télévisions	/-----/

C10Q4: Climatiseurs	/-----/
C10Q5: Machine à laver	/-----/
C10Q6: Ventilateurs	/-----/
C10Q7: Portable	/-----/
C10Q8: Ordinateurs (portable et bureau)	/-----/
C10Q9: Micro-ondes	/-----/
C10Q10: Fer à repasser	/-----/
C10Q11: Moulinex	/-----/
C10Q12: Voiture électrique ou hybride	/-----/
C10Q13: Moto électrique	/-----/
C11 : Le caractère énergivore rentre-t-il dans le choix des appareils électroménagers ?	1. Oui 2. Non
C12: A quelle fréquence accomplissez-vous les gestes suivants dans votre vie quotidienne ?	1. Jamais 2. Occasionnellement 3. Souvent 4. Tout le temps 5. Ne sait pas/ne s'applique pas
C12Q1: Eteindre les lumières en quittant une pièce	/-----/
C12Q2: Baisser la climatisation pour limiter votre consommation d'énergie	/-----/
C12Q3: Coupe le mode veille des appareils électroménagers/électroniques	/-----/
C12Q4: Travailler en mode meilleur rendement énergétique sur vos appareils électroniques	/-----/
C13: Avez-vous installé au cours de ces dix dernières années dans votre résidence principale les éléments suivants :	1. Oui 2. Non 3. Il en était déjà équipé 4. Impossible (irréalisable dans ma résidence ou ce serait à mon propriétaire d'en installer)
C13Q1: Ampoules basse consommation (fluocompactes, LED)	/-----/
C13Q2: Panneaux solaires pour électricité	/-----/
C13Q3: Appareil électroménagers économes en énergies	/-----/
C14: Si oui, à quel coût approximatif ?	
C14Q1: Ampoules basse consommation (fluocompactes, LED)	---------FCFA
C14Q2: Panneaux solaires pour électricité	---------FCFA
C14Q3: Appareil électroménagers économes en énergies	---------FCFA
C15: Pour ces installations, avez-vous reçu une aide financière quelconque ?	1. Oui, Gouvernementale 2. Oui, ONG 3. Oui, Familiale

	4. Non
C15Q1: Ampoules basse consommation (fluocompactes, LED)	/-----/
C15Q2: Panneaux solaires pour électricité	/-----/
C15Q3: Appareil électroménagers économes en énergies	/-----/
C16 : Avez-vous obtenu des facilités de payement lors du payement de ces installations ?	1. Oui 2. Non
C17 : Si oui, quelles sont ces facilités ?	…….
C15: Dans quelle mesure les facteurs suivants vous encourageraient-ils à réduire votre consommation d'énergie	1. Très important 2. Important 3. Moins important 4. Pas importante 5. Ne sait pas
C15Q1: Plus d'information pratiques sur les manières de réduire notre consommation énergétique	/-----/
C15Q2: Augmentation du prix de l'énergie	/-----/
C15Q3: Plus d'information sur l'impact de notre consommation sur l'environnement	/-----/
C15Q4: Plus d'information sur la consommation énergétique de mon foyer	/-----/
C15Q5: Découvrir que mon foyer consomme plus que d'autres foyers similaires	/-----/
C15Q6: Identification plus facile des appareils écoénergétiques	/-----/
C15Q7: Investissement dans les équipements économes en énergie moins coûteux	/-----/
C16 : Dans quelle mesure ces facteurs sont/seront ils importants dans votre choix de voiture/moto	1. Pas important 2. Moins important 3. Important 4. Très important 5. Ne sait pas
C16Q1 : Prix	/-----/
C16Q2 : Consommation de carburant	/-----/
C16Q3 : Confort	/-----/
C16Q4 : Impact sur l'environnement	/-----/
C16Q5 : Sécurité	/-----/
C16Q6 : Fiabilité et performance	/-----/
C16Q7 : Attirance pour la marque	/-----/

C17 : Quelle somme seriez-vous prêt(e) à payer en plus pour une voiture/moto électrique par rapport aux prix de leurs marques conventionnelles	
C17Q1 : Moto	-----%
C17Q2 : Voiture	-----%
C18 : Pourquoi ne souhaitez-vous pas payer davantage pour une voiture/moto électrique ?	1. Pas du tout d'accord 2. Pas d'accord 3. D'accord 4. Tout à fait d'accord 5. Sans opinion
C18Q1 : Si j'avais plus d'argent, je le ferai	/-----/
C18Q2 : Je préfère les conventionnelles	/-----/
C18Q3 : Manque d'installations de recharge	/-----/
C18Q4 : Ces modèles sont incommodes en raison de leur besoin d'être fréquemment rechargés	/-----/
C18Q5 : Je ne pense pas qu'ils ont des avantages environnementaux	/-----/
C18Q6 : Je ne pense pas que je devrai payer plus cher	/-----/

Partie D : Politique d'atténuations du changement climatique et de promotion des énergies renouvelables

D1 : Avez déjà entendu parler du changement climatique ?	1. Oui 2. Non
D2 : Où avez-vous déjà écouté parler du changement climatique ?	1. Radio 2. Télévision 3. Sensibilisation 4. Ecole 5. Autre ………………………
D3 : En examinant la régularité des pluies ces 20 dernières années (2000-2023), avez-vous remarqué un changement dans la régularité des pluies ?	1. Oui 2. Non
D4 : Si Oui, dans quel sens ?	1. Augmentée 2. Diminuée 3. Rester inchangées 4. Ne sait pas
D5 : Avez-vous constaté un arrêt de la pluie en pleine saison des cultures pendant la dernière campagne ?	1. Oui 2. Non

D6 : Quel changement dans les températures avez-vous constaté au cours de ces deux dernières décennies (20 ans)	1. Augmenté/fait trop chaud 2. Diminué/fait trop frais 3. Constante/rien n'a vraiment changé 4. Ne sait pas
D7 : Votre localité a-t-elle connue une/des vague(s) de sécheresse durant la dernière campagne agricole ?	1. Oui 2. Non
D8 : A-t-elle affecté vos cultures ?	1. Perte de culture 2. Reduction des rendements 3. Autre(s)
D8 : Pensez-vous que le fait d'utiliser l'énergie solaire et les foyers améliorés est-il solution pour lutter contre le changement climatique ?	1. Oui 2. Non
D10 : Connaissez-vous les politiques gouvernementales de transition énergétique et de lutte contre le changement climatique ?	1. Oui 2. Non 3. Pas d'opinion
D10Q1 : Mobilité verte (Moto et voiture électriques ou hybrides)	/-----/
D10Q2 : Augmentation du couvert forestier (reboisement et interdiction de la déforestation)	/-----/
D10Q3 : Protection des côtes contre l'érosion	/-----/
D10Q4 : Programme d'électrification rurale	/-----/
D 13 : votre localité a-t-elle bénéficié d'un projet d'électrification dans cette optique au cours de ces 5 dernières années ?	1. Oui 2. Non 3. Ne sait pas
D14 : Si oui/ quel type de projet d'électrification avez-vous bénéficier ?	1. Réseau électrique 2. Mini-réseau local 3. Kits solaires 4. Panneau Solaire 5. Autre…………………
D15 : Avez-vous payé une somme ou fait un don de toute nature afin de bénéficier de ce projet ?	1. Oui 2. Non
Que pensez-vous des débats sur énergies ?	…………………………………………….
Que pensez-vous des débats le climat et l'environnement ?	……………………………………………

Dynamic Computable General Equilibrium: Mathematical structure

The model is based on GAMS software using the Non-linear Problem (NLP) solver. It consists of six blocks: production block, incomes and savings block, demand block, trade block, market-clearing and macroscopic closure block, and macro-indicator block. Following Jia & Lin (2022), we consider the PEP-1-t model which is the 7-tier nested production technology. The other input parts are CES production technology except that Leontief production technology is applied to the aggregated intermediate input. The production process in the PEP-1-t model is structured hierarchically using a nested framework.

1. **Production block**

At the top level, aggregate output combines value-added and intermediate inputs using a Leontief production function, which assumes no substitutability. Firms are assumed to operate in a perfectly competitive environment. So each industry's representative firm maximizes profits subject to its production technology, while it considers the prices of goods and services and factors as given (price-taking behavior). The set of productive activities is represented by the index *J*. At the top level, the sectoral output of each productive activity *j* combines value added and total intermediate consumption in fixed shares. Value-added is composed of composite labor and capital, linked via a constant elasticity of substitution (CES) function, which allows for some substitutability.

$$VA_{j,t} = v_j XST_{j,t} \#(\{seq\ num\})$$

$$CI_{j,t} = io_j XST_{j,t}$$

At the second level, each industry's value added consists of composite labor and composite capital, following a constant elasticity of substitution (CES) specification

$$VA_{j,t} = B_j^{VA}\left[\beta_j^{VA} LDC_{j,t}^{-\rho_j^{VA}} + (1-\beta_j^{VA}) KDC_{j,t}^{-\rho_j^{VA}}\right]^{\frac{-1}{\rho_j^{VA}}}$$

$$LDC_{j,t} = \left[\frac{\beta_j^{VA}}{1-\beta_j^{VA}} \frac{RC_{j,t}}{WC_{j,t}}\right]^{\sigma_j^{VA}} KDC_{j,t}$$

Profit maximization (or cost minimization) by the firms leads them to employ labor and capital to the point where the value marginal product of each is equal to its price (the wage rate and the rental rate of capital, respectively). At the bottom level, labor and capital are further disaggregated into types, each also combined using CES functions. On the value-added side, the various categories of labor, indexed as *L*, are combined following a constant elasticity of substitution (CES) technology, which reflects the imperfect substitutability between different types of labor. The firm chooses its labor composition so as to minimize its labor cost given the relative wage rates. Labor demand of each type derives from the first-order conditions of cost minimization by the representative firm, subject to the CES technology.

$$LDC_{j,t} = B_j^{LD}\left[\sum_l \beta_{l,j}^{LD} LD_{l,j,t}^{-\rho_j^{LD}}\right]^{\rho_j^{\frac{-1}{LD}}}$$

$$LDC_{l,j,t} = \left[\frac{\beta_{l,j}^{LD} WC_{j,t}}{WTI_{l,j,t}}\right]^{\sigma_j^{LD}} \left(B_j^{LD}\right)^{\sigma_j^{LD}-1} LDC_{j,t}$$

Likewise, composite capital is a CES combination of the different categories of capital, indexed as *K*. As in the case of labor, it is assumed that different categories of capital are imperfect substitutes. The demand for each type of capital results from cost minimization

$$KD_{j,t} = B_j^{KD}\left[\sum_k \beta_{k,j}^{KD} KD_{k,j,t}^{-\rho_j^{KD}}\right]^{\rho_j^{\frac{-1}{KD}}}$$

$$KD_{k,j,t} = \left[\frac{\beta_{l,j}^{KD} RC_{j,t}}{RTI_{l,j,t}}\right]^{\sigma_j^{KD}} \left(B_j^{KD}\right)^{\sigma_j^{KD}-1} KDC_{j,t}$$

Intermediate consumption comprises various goods and services combined in fixed proportions. The model captures the cost-minimizing behavior of firms in choosing input combinations based on relative prices. Returning to the second level, but on the intermediate consumption side, aggregate intermediate consumption is made up of various goods and services. Here it is assumed that intermediate inputs are perfectly complementary and are combined following a Leontief production function.

$$DI_{i,j,t} = aij_{i,j} CI_{j,t}$$

2. Income and savings block

2.1.Households

The PEP-1-t model offers the possibility of several categories of households and businesses, respectively indexed as H, and F, together with government, designated as GVT, and the rest of the world, ROW.

Income generation and savings are analyzed across households, businesses, the government, and the rest of the world. Households derive income from labor, capital, and transfers, and allocate it between consumption, savings, and taxes. Therefore, household total incomes (*$Yh_{h,t}$*) are the sum of labor income (*$YHL_{h,t}$*), capital income (*$YHK_{h,t}$*), and transfers received from other agents (*$YHTR_{h,t}$*). Each household type receives a fixed share λ^{WL} of the earnings of each type of labor. Likewise, total capital income is distributed between agents, including households, in fixed proportions λ^{RK}. Finally, transfer income is simply the sum of all transfers (*$TR_{h,ag,t}$*) received by type *h* households.

$$YH_{h,t} = YHL_{h,t} + YHK_{h,t} + YHTR_{h,t}$$

$$YHL_{h,t} = \sum_{l} \lambda_{h,l}^{WL} \left(W_{l,t} \sum_{j} LD_{l,j,t} \right)$$

$$YHK_{h,t} = \sum_{k} \lambda_{h,k}^{RK} \left(\sum_{j} R_{k,j,t} KD_{k,j,t} \right)$$

$$YHTR_{h,t} = \sum_{ag} TR_{h,ag,t}$$

Subtracting direct taxes ($DTH_{h,t}$) and household transfers to government ($TR_{gvt.h,t}$) yields type h household disposable income ($YDH_{h,t}$). Indeed, since household transfers to government are mostly contributions to various social programs, our calculation of disposable income is consistent with national accounts. Whatever disposable income is left after savings (*$SH_{h,t}$*) and transfers to other agents (*$TR_{agng,h}$*) is entirely dedicated to consumption.

Household savings are a linear function of disposable income, and allows for the marginal propensity to save (*$sh1_h$*) to be different from the average propensity. But in a growing economy, the relative size of the intercept will diminish with time, unless the intercept itself is assumed to grow at the same rate. This is why the intercept has a time subscript. In the default specification of PEP-1-t, the intercept grows each period at the same rate as population index. In addition, it possible to fully of partially index the intercept (*sh0h*) to changes in the consumer price index (*PIXCON*) . This is especially useful for testing the model's homogeneity, in which case price elasticity η is set to 1. Household transfers to non-government agents are simply proportional (λ^{TR}) to disposable income. As for household transfers to government, they are akin to social program contributions: as such, they are treated in the same way as household income taxes, i.e. they are described as a linear function of total income (with *tr0h* being the intercept, and *$tr1_h$* the sslope)

$$YDH_{h,t} = YH_{h,t} - TDH_{h,t} - TR_{gvt,h,t}$$

$$CTH_{h,t} = YDH_{h,t} - SH_{h,t} - \sum_{agng} TR_{agng,h,t}$$

$$SH_{h,t} = PIXCON_t^{\eta} sh0_{h,t} + sh1_{h,t} YDH_{h,t}$$

$$TR_{agng,h,t} = \lambda_{agng,h}^{TR} YDH_{h,t}$$

$$TR_{gvt,h,t} = PIXCON_t^{\eta} tr0_{h,t} + tr1_{h,t} YH_{h,t}$$

2.2.Firms

Business incomes are derived from capital returns and transfers, with taxes subtracted to yield disposable income. Business total income ($Yf_{f,t}$) is the sum of capital income ($YFK_{f,t}$), and transfers received from other agents ($YFTR_{f,t}$).

$$YF_{f,t} = YFK_{f,t} + YFTR_{f,t}$$

$$YFK_{f,t} = \sum_{k} \lambda_{f,k}^{RK} \left(\sum_{j} R_{k,j,t} KD_{k,j,t} \right)$$

$$YFTR_{f,t} = \sum_{ag} TR_{f,ag,t}$$

Deducting business income taxes ($DTF_{f,t}$) from total income yields the disposable income ($YDF_{f,t}$) of each type of business. Likewise, business savings ($SF_{f,t}$) are the residual that remains after subtracting transfers to other agents from disposable income. Finally, business transfers to other agents are simply proportional to disposable income

$$YDF_{f,t} = YF_{f,t} - TDF_{f,t}$$

$$SF_{f,t} = YDF_{f,t} - \sum_{ag} TR_{ag,f,t}$$

$$TR_{ag,f,t} = \lambda_{ag,f}^{TR} YDF_{f,t}$$

2.3.Government

Government revenues stem from various taxes (on income, production, and imports) and capital returns, while expenditures include transfers and public consumption. Similarly to what has been done with household savings, income taxes are described as a linear function of total income, whether it be for households or for businesses. That way, when a non-zero intercept ($ttdh0_{h,t}$ and $ttdf0_{f,t}$) is applied, the marginal rate of taxation ($ttdh1_{h,t}$ and $ttdf1_{f,t}$) is different from the average rate. Just as in the household savings equation, the income tax intercepts are time-indexed, and, in the default specification, they grow each period at the same rate as population index

$$TDHT_t = \sum_h TDH_{h,t}$$

$$TDH_{h,t} = PIXCON_t^{\eta} ttdh0_{h,t} + ttdh1_{h,t} YH_{h,t}$$

$$TDFT_t = \sum_f TDF_{f,t}$$

$$TDF_{f,t} = PIXCON_t^{\eta} ttdf0_{f,t} + ttdf1_{f,t} YFK_{f,t}$$

As mentioned earlier, the model allows for taxes on production factors (payroll taxes and capital taxes), as well as for taxes on production itself (together, these three forms of taxation constitute other taxes on production). The rates of taxation are time-indexed to facilitate the simulation of scenarios in which fiscal policy changes through time. First, as regards taxes on factors of production, the model notation distinguishes tax rates by industry, and also by type of labor or capital. Each rate, $ttiw_{l,j,t}$ for payroll and $ttik_{k,j,t}$ for capital then applies to the corresponding. Next, a tax ($ttip_{j,t}$) may be applied to the total value of production ($PP_{j,t}\ XST_{j,t}$).

$$TIW_{l,j,t} = ttiw_{l,j,t} W_{l,t} LD_{l,j,t}$$

$$TIWT_t = \sum_{l,j} TIW_{l,j,t}$$

$$TIK_{k,j,t} = ttik_{k,j,t} R_{k,j,t} KD_{k,j,t}$$

$$TIKP_t = \sum_{k,j} TIK_{k,j,t}$$

$$TIP_{j,t} = ttip_{j,t} PP_{j,t} XST_{j,t}$$

$$TIPT_t = \sum_j TIP_{j,t}$$

Indirect taxes on commodities (index i) apply on the sales value including margins and custom duties whenever the latter exist. It includes the price $PL_{i,t}$ of local products i (excluding taxes and margins), the price $PL_{i,t} + \sum_{ij} PC_{ij,t} tmrg_{ij,t}$ of local products i (including taxes and margins), the world price $PWM_{i,t}$ of imported products i (expressed in foreign currency), the world price $PWM_{i,t} e_t$ of imported products i (expressed in local currency)

$$TIC_{i,j} = ttic_{i,j}\left[\left(PL_{i,t} + \sum_{ij} PC_{ij,t}tmrg_{ij,t}\right)DD_{j,t} + \left(\left(1 + ttim_{i,t}\right)PWM_{i,t}e_t + \sum_{ij} PC_{ij,t}tmrg_{ij,t}\right)IM_{i,t}\right]$$

$$TICT_t = \sum_i TIC_{i,t}$$

The value of local purchases of i (including margins) is $\left(PL_{i,t} + \sum_{ij} PC_{ij,t}tmrg_{ij,t}\right)DD_{j,t}$

The price of imported products i (including imported duties) is $\left(1 + ttim_{i,t}\right)PWM_{i,t}e_t$

The price of imported products i (including imported duties and margins) is $\left(1 + ttim_{i,t}\right)PWM_{i,t}e_t + \sum_{ij} PC_{ij,t}tmrg_{ij,t}$

The value of imported products i (including imported duties and margins) is $\left(\left(1 + ttim_{i,t}\right)PWM_{i,t}e_t + \sum_{ij} PC_{ij,t}tmrg_{ij,t}\right)IM_{i,t}$

Other taxes collected are taxes and duties on imported products ($TIM_{i,t}$), and on exports ($TIX_{i,t}$).

$$TIMT_t = \sum_i TIM_{i,t}$$

$$TIM_{i,t} = ttim_{i,t}PWM_{i,t}e_tIM_{i,t}$$

$$TIXT_{i,t} = \sum_i TIX_{i,t}$$

$$TIX_{i,t} = ttix_{i,t}\left(PE_{i,t} + \sum_{ij} PC_{ij,t}tmrg^X_{ij,i}\right)EXD_{i,t}$$

Transfers paid by the government, $TR_{agng,gvt,t}$, to other agents are initially set equal to their SAM values, $TR0$, and they grow each period at the same rate n_t as population index pop_t, and are indexed, fully or partially, to the consumer price index. The current government budget surplus or deficit (positive or negative savings, SG_t) is the difference between its revenue and its expenditures. The latter consists of transfers to agents and current expenditures on goods and services, G_t.

$$TR_{agng,gvt,t} = PIXCON_t^{\eta}TR^O_{agng,gvt}pop_t$$

$$SG_t = YG_t - \sum_{agng} TR_{agng,gvt,t} - G_t$$

2.4.The rest of the world

The rest of the world interacts through trade and transfers, with net savings reflecting the current account balance. The rest of the world receives payments for the value of imports, part of the income of capital, and transfers from domestic agents. Transfers paid by foreigners to other domestic agents, $TR_{agd,row\ ,t}$, are initially set equal to their SAM valuesTR^0, and they grow each period at the same rate n_t as population index pop_t,, and are indexed to the consumer price index. Foreign spending in the domestic economy consists of the value of exports, and transfers to domestic agents. The difference between foreign receipts ($YROW_t$) and spending is the amount of rest-of-the-world savings ($SROW_t$), which are equal in absolute value to the current account balance (CAB_t), but of opposite sign.

$$YROW_t = e_t \sum_i PWM_{i,t} IM_{i,t} + \sum_k \lambda_{row,t}^{RK} \left(\sum_j R_{k,j,t} KD_{k,j.i} \right) + \sum_{agd} TR_{Row,agd,t}$$

$$TR_{Row,agd,t} = PIXCON_t^{\eta} TR_{agd,row}^{O} pop_t$$

$$SROW_t = YROW_t - \sum_i PE_{i,t}^{FOB} EXD_{i,t} - \sum_{agd} TR_{agd,row,t}$$

$$SROW_t = -CAB_t$$

3. Demand block

Demand for goods and services includes household consumption, investment, government spending, and margins (trade and transport).

3.1.Household consumption demand

Household consumption is modeled using a Stone-Geary utility function, which allows for subsistence consumption and variable elasticities. Contrary to Cobb-Douglas utility functions, often used in the literature, this specification imposes neither zero cross-price elasticities between all pairs of goods, nor unit income-elasticities for all goods. Thus, it offers a degree of flexibility with respect to substitution possibilities in response to relative price changes.

$$PC_{i,t} C_{i,h,t} = PC_{i,t} C_{i,h,t}^{MIN} + \gamma_{i,h}^{LES} \left(CTH_{h,t} - \sum_{ij} PC_{ij,t} C_{ij,h,t}^{MIN} \right)$$

Type h household demand for each good, $C_{i,h,t}$, is determined by utility maximization subject to the budget constraint. A characteristic of these utility functions is that there is a minimum level of consumption of each commodity, $C_{i,h,t}^{MIN}$, (which may be zero for some commodities).

3.2.Demand by public administrations

Government demand for goods is similarly determined based on a fixed budget and prices. Current expenditure budget is distributed among commodities in fixed shares γ^{GVT}. The quantity demanded of each commodity, $CG_{i,t}$, varies inversely with its price.

$$PC_{i,t}CG_{i,t} = \gamma_i^{GVT} G_t$$

3.3.Investment demand

Investment demand, split into gross fixed capital formation (GFCF) and inventory changes, is endogenous and price sensitive. GFCF expenditure is obtained by subtracting the cost of changes in inventories ($VSTK_{i,t}$) from total investment expenditure (IT_t)

$$GFCF_t = IT_t - \sum_i PC_{i,t} VSTK_{i,t}$$

Both private and public investment are distributed among commodities in fixed shares (γ^{INVPRI} and γ^{INVPUB}, respectively); implicitly, the production function of new capital is Cobb-Douglas. So, for a given amount of investment expenditures, the quantity demanded of each commodity i for investment purposes of either kind is inversely related to its purchaser price.

$$PC_{i,t}INV_{i,t}^{PRI} = \gamma_i^{INVPRI} IT_t^{PRI}$$

$$PC_{i,t}INV_{i,t}^{PUB} = \gamma_i^{INVPUB} IT_t^{PUB}$$

The quantity demanded of each commodity i for investment purposes is the sum of the quantity demanded for private investment and for public investment.

$$INV_{i,t} = INV_{i,t}^{PRI} + INV_{i,t}^{PUB}$$

3.4.Intermediate demand

Intermediate and margin demands depend on production and trade volumes, respectively. Intermediate demand for each commodity ($DIT_{i,t}$) is the sum of industry demands ($DI_{i,j,t}$).

$$DIT_{i,t} = \sum_j DI_{i,j,t}$$

3.5.Demand as transport or trade margins

Producers allocate their output between products and markets using CET functions, reflecting imperfect transformability among products and markets. Margin rates are applied to the volume of domestic production and imports to determine the quantities of these margin services (*$MRGN_{i,t}$*) required to distribute commodities to buyers.

$$MRGN_{i,j} = \sum_{ij} tmrg_{i,ij} DD_{ij,t} + \sum_{ij} tmrg_{i,ij} IM_{ij,t} + \sum_{ij} tmrg_{i,ij}^{X} EXD_{ij,t}$$

4. Trade block

Exports and domestic supply are modeled based on revenue maximization, with the small-country hypothesis assuming exogenous world prices. Domestic demand integrates imports and local products via CES aggregation, indicating imperfect substitutability. The model accommodates price responsiveness for both imports and exports, reflecting elasticity conditions. Producers allocate output among products so as to maximize sales revenue, given product prices, subject to the CET function. Individual product supply functions are derived from the first-order conditions of revenue maximizing.

$$XST_{j,t} = B_j^{XT} \left[\sum_i \beta_{j,t}^{XT} XS_{j,i,t}^{\rho_j^{XT}} \right]^{\rho_j^{\frac{1}{XT}}}$$

$$XS_{j,i,t} = \frac{XST_{j,t}}{\left(B_j^{XT}\right)^{1+\sigma_j^{XT}}} \left[\frac{P_{j,i,t}}{\beta_{j,i}^{XT} PT_{j,t}} \right]^{\sigma_j^{XT}}$$

Next, the output of every product of an industry is shared out among markets (domestic or export), again with the goal of maximizing the firm’s total revenue, given the demand in each market and the various taxes that apply. It is assumed that production directed to one market is somewhat different from production directed to another market. This imperfect substitutability is represented in PEP-1-t by means of a constant elasticity of transformation (CET) aggregator function that describes how readily production can be redirected from one market to another.

$$XS_{j,i,t} = B_{j,i}^{X} \left[\beta_{j,i}^{X} EX_{j,i,t}^{\rho_{j,i}^{X}} + \left(1 + \beta_{j,i}^{X}\right) DS_{j,i,t}^{\rho_{j,x}^{X}} \right]^{\rho_{j,i}^{\frac{1}{X}}}$$

$$EX_{j,i,t} = \left[\frac{1 - \beta_{j,i}^{X}}{\beta_{j,i}^{X}} \frac{PE_{i,t}}{PL_{i,t}} \right]^{\sigma_{j,i}^{X}} DS_{j,i,t}$$

$$EXD_{i,t} = EXD_i^0 pop_t \left(\frac{e_t PWX_{i,t}}{PE_{i,t}^{FOB}}\right)^{\sigma_i^{XD}}$$

Relative supply functions are derived from the first-order conditions of revenue maximizing subject to the CET aggregator function. Local producer can increase his share of the world market only by offering a price that is advantageous relative to the (exogenous) world price.

Buyer behavior is symmetrical to producer behavior, in that it is assumed that local products are imperfect substitutes for imports, or, in other words, that goods are heterogenous with respect to their origin. So commodities demanded on the domestic market are composite goods, combinations of locally produced goods and imports. The imperfect substitutability between the two is represented by a constant elasticity of substitution (CES) aggregator function. Just as sellers seek to maximize revenue, buyers minimize expenses, subject to the CES aggregation function. Relative demand functions derive from the first-order optimum conditions.

$$Q_{i,t} = B_i^M \left[\beta_i^M IM_{i,t}^{-\rho_i^M} + (1-\beta_i^M) DD_{i,t}^{-\rho_i^M}\right]^{\frac{-1}{\rho_i^M}}$$

$$IM_{i,t} = \left[\frac{\beta_i^M}{1-\beta_i^M}\frac{PD_{i,t}}{PM_{i,t}}\right]^{\sigma_i^M} DD_{i,t}$$

5. **Market-clearing and macroscopic closure block**

Price determination in the model incorporates both cost-based and market-based elements. Aggregate prices are weighted averages of component prices, adjusted for taxes and margins. Production prices include taxes on production and factor use. Prices of composite commodities reflect domestic and import sources, adjusted for taxes and exchange rates. The model also defines key price indices, including the GDP deflator, consumer price index, investment price index, and government expenditure price index, to analyze inflationary dynamics.

The different prices and price indexes naturally depend on the hypotheses and functional forms already stated. In aggregations, the price of an aggregate is a weighted sum of the prices of its components. The weights are determined by equating the value of the aggregate to the sum of the values of its components, given the quantity of the aggregate (which is determined from the aggregator function). The weight assigned the price of each component is therefore the ratio of its volume (or quantity) to the volume (or quantity) of the aggregate. Only in Leontief fixed-proportions aggregations are the weights invariant to relative price changes; in other cases, component proportions, and, consequently, component price weights, change in response to relative price changes, and they change more or less sharply, depending on the elasticity of substitution or transformation. For instance, the unit cost of an industry's output (including taxes directly related to the use of capital and labor, but excluding other taxes on production) is a weighted sum of the prices of value added and aggregate intermediate consumption.

$$PP_{j,t} = \frac{PVA_{j,t}VA_{j,t} + PCI_{j,t}CI_{j,t}}{XST_{j,t}}$$

$$PT_{j,t} = \left(1 + ttip_{j,t}\right)PP_{j,t}$$

Here, the weights are $Va_{j,t}/XST_{j,t}$ and $Ci_{j,t}/XST_{j,t}$. Multiplying both sides of the equation by $XST_{j,t}$ yields the value accounting identity $PP_{j,t}\, XST_{j,t} = PVA_{j,t}\, Va_{j,t} + PCI_{j,t}\, Ci_{j,t}$. The same principle applies to the prices of other aggregates. The basic price of production ($PT_{j,t}$) is obtained from the unit cost by adding taxes on production (other than taxes on labor or capital, already included in the unit cost).

The price of aggregate intermediate consumption is a combination of the commodity prices of the industry's intermediate inputs.

$$PCI_{j,t} = \frac{\sum_i PC_{i,t}DI_{i,j,t}}{CI_{j,t}}$$

Similarly, the price of value added is a combination of the prices of composite labor and composite capital.

$$PVA_{j,t} = \frac{WC_{j,t}LDC_{j,t} + RC_{j,t}KDC_{j,t}}{VA_{j,t}}$$

The price of an industry's composite labor is a weighted sum of the wage rates (including payroll taxes) of the different categories of labor used by that industry. Wages paid by industry differ from wages received by workers by the amount of payroll taxes.

$$WC_{j,t} = \frac{\sum_l WTI_{l,j,t}LD_{l,j,t}}{LDC_{j,t}}$$

$$WTI_{l,j,t} = W_{l,t}\left(1 + ttiw_{l,j,t}\right)$$

In the same way, the price of an industry's composite capital is a weighted sum of the rental rates of the different types of capital used by that industry. The rental rate of capital paid by industry differ from the one received by capital owners by the amount of capital taxes.

$$RC_{j,t} = \frac{\sum_k RTI_{k,j,t} KD_{k,j,t}}{KDC_{j,t}}$$

$$RTI_{k,j,t} = R_{k,j,t}\left(1 + ttik_{k,j,t}\right)$$

Exporting industries have the possibility of selling their output on the international market or the domestic market. So the price of their aggregate production is a weighted sum of the price obtained on each market, following the price aggregation principle. The weight assigned to each market is proportional to the quantity sold on that market. These weights vary in response to relative price changes, more or less sharply, depending on the elasticity of transformation in the CET.

$$PT_{j,t} = \frac{\sum_i P_{j,i,t} XS_{j,i,t}}{XST_{j,t}}$$

The basic price obtained by industry *j* for product *i* is a weighted sum of its basic price on the domestic market and its basic price on the export market. The FOB price paid by purchasers on the export market is different from the one received by the producer, since margins and export taxes must be added on.

$$P_{j,i,t} = \frac{PE_{i,t} EX_{j,i,t} + PL_{i,t} DS_{j,i,t}}{XS_{j,i,t}}$$

$$PE_{i,t}^{FOB} = \left(PE_{i,t} + \sum_{ij} PC_{ij,t} tmrg_{ij,i}^{X} \right)\left(1 + ttix_{i,t}\right)$$

The price paid for the local product is the sum of the price received by the producer, margins, and indirect taxes.

$$PD_{i,t} = \left(1 + ttic_{i,t}\right)\left(PL_{i,t} + \sum_{ij} PC_{ij,t} tmrg_{ij,i} \right)$$

Similarly, the price paid for the imported product is the world price, translated into the local currency, plus taxes and duties on imports, margins, and domestic indirect taxes.

$$PM_{i,t} = \left(1 + ttic_{i,t}\right)\left(\left(1 + ttim_{i,t}\right) e_t PWM_{i,t} + \sum_{ij} PC_{ij,t} tmrg_{ij,i} \right)$$

As was previously explained, commodities purchased on the domestic market are composites. The price of the composite is a weighted sum of the price paid for domestically produced, and imported goods.

$$PC_{i,t} = \frac{PM_{i,t}IM_{i,t} + PD_{i,t}DD_{i,t}}{Q_{i,t}}$$

Finally, four price indexes have been defined:

The GDP deflator is a Fisher index: $PIXGDP_t = \sqrt{\frac{\sum_j PVA_{j,t}VA_j^0 \sum_j PVA_{j,t}VA_{j,t}}{\sum_j PVA_j^0 VA_j^0 \sum_j PVA_j^0 VA_{j,t}}}$

The consumer price is a Laspeyres index: $PIXCON_t = \frac{\sum_j PC_{i,t} \sum_h C_{i,h}^0}{\sum_{ij} PC_{ij}^0 \sum_h C_{ij,h}^0}$

The three other ones are exact price indexes, dual to the Cobb-Douglas functions which describe commodity demand for investment purposes and for public consumption.

$$PIXINV_t^{PRI} = \prod_i \left(\frac{PC_{i,t}}{PC_i^0}\right)^{\gamma_i^{INVPRI}}$$

$$PIXINV_t^{PUB} = \prod_i \left(\frac{PC_{i,t}}{PC_i^0}\right)^{\gamma_i^{INVPUB}}$$

$$PIXGVT_t = \prod_i \left(\frac{PC_{i,t}}{PC_i^0}\right)^{\gamma_i^{GVT}}$$

6. Macro-indicator block: Equilibrium

Whether it be for the goods and services market or the factor market, supply and demand equilibrium must be verified. Likewise, total investment expenditure must be equal to the sum of agents' savings. The sum of supplies of every commodity by local producers must be equal to the domestic demand for that commodity produced locally. And finally, supply to the export market of each good must be matched by demand.

- ✓ Market for commodities: $Q_{i,t} = \sum_h C_{i,h,t} + CG_{i,t} + INV_{i,t} + VSTK_{i,t} + DIT_{i,t} + MRGN_{i,t}$
- ✓ Labor market: $\sum_j LD_{l,j,t} = LS_{l,t}$
- ✓ Capital market: $\sum_j KD_{k,j,t} = KS_{k,t}$
- ✓ Investment – savings: $IT_t = \sum_h SH_{h,t} + \sum_f SF_{f,t} + SG_t + SROW_t$
- ✓ Domestic market: $\sum_j DS_{j,i,t} = DD_{i,t}$
- ✓ Export market: $\sum_j EX_{j,i,t} = EXD_{i,t}$

7. Gross Domestic Product

GDP at basic prices is equal to payments made to factors, plus taxes on production other than taxes on labor or capital already included in factor costs.

$$GDP_t^{BP} = \sum_j PVA_{j,t} VA_{j,t} + TIPT_t$$

GDP at market prices exceeds GDP at basic prices by exactly the amount of taxes on products and imports.

$$GDP_t^{MP} = GDP_t^{BP} + TPRCTS_t$$

As for GDP at market prices from the income perspective, it is equal to the sum total of income paid to labor and to capital, plus taxes on products and imports, plus other taxes on production.

$$GDP_t^{IB} = \sum_{l,j} W_{l,t} LD_{l,j,t} + \sum_{k,j} R_{k,j,t} KD_{k,j,t} + TPRODN_t + TPRCTS_t$$

On the other hand, GDP at market prices from the final demand perspective is the sum of net final expenditures: household consumption, current public expenditures on goods and services, investment expenditures, plus the value of exports, minus the value of imports.

$$GDP_t^{FD} = \sum_i PC_{i,t} \left[\sum_h C_{i,h,t} + CG_{i,t} + INV_{i,t} + VSTK_{i,t} \right] + \sum_i PE_{i,t}^{FOB} EXD_{i,t} - \sum_i e_t PWM_{i,t} IM_{i,t}$$

8. Dynamic equations

PEP-1-t is a recursive dynamic model, which means that the underlying behavioral assumptions do not involve any intertemporal optimization, as opposed to intertemporal dynamic models, where they do. So, in PEP-1-t, each period is solved as a static equilibrium, subject to the variables inherited from the preceding period. The dynamic equations define how the variables that link each period to the next evolve between periods. Dynamic assignments constitute the link from one period to the next. They fall into two categories: one set of statements update variables that grow at a constant rate per period; the other equations control the accumulation of capital.

8.1. Accumulation of capital

Total investment is determined by the savings-investment equilibrium constraint, with savings endogenous. As seen previously, GFCF expenditure is obtained by subtracting the cost of changes in inventories from total investment expenditure. GFCF includes both private and public investments, which translate into greater capital stock at the following period.

Given the price of public investment, PK^{PUB}, the amount of public investment expenditures, IT^{PUB}, can be determined.

$$IT_t^{PUB} = PK_t^{PUB} \sum_{k,pub} IND_{k,pub,t}$$

The price of public investment follows from investment demand function whose forms imply that the production function of new capital is Cobb-Doublas.

$$PK_t^{PUB} = \frac{1}{A^{K\_PUB}} \prod_i \left[\frac{PC_{i,t}}{\gamma_i^{INVPUB}}\right]^{\gamma_i^{INVPUB}}$$

Here we further assume that new public capital is of the « putty-clay » kind: when the investment expenditure is incurred, the aggregate quantity of new private capital produced may be frictionlessly transformed into any type *k* capital, destined to any public sector industry *pub*; once the new capital has been allocated, however, it becomes fixed.

$$KD_{k,pub,t+1} = KD_{k,pub,t}\left(1 - \delta_{k,pub}\right) + IND_{k,pub,t}$$

This specification implies that the price of one unit of new capital stock is the same, regardless of its type *k* or the industry *pub* in which it is installed. That is why the variable has no other index than time index *t*. Of course, the calibration of the capital stock has to be consistent with that specification. The stock of type *k* capital in industry *pub* in period $t + 1$ is equal to the stock of the preceding period, minus depreciation, plus the volume of new capital investment in the preceding period. The underlying time-structure is therefore that new capital comes on-line one period after the investment has been made.

The first equation determines how much savings are taken up by public investment, and given that changes in inventories are assumed to grow at the same rate as the population, this equilibrium determines how much is left for private (business sector) investment. Given the price of private investment, the volume of new private capital investment is thus constrained by the level of private investment. The price of private investment demand function whose forms imply that the production function of new capital is Cobb-Doublas. Private investment follows the same « putty-clay » assumption as for public investment.

$$IT_t^{PRI} = IT_t - IT_t^{PUB} - \sum_i PC_{i,t} VSTK_{i,t}$$

$$IT_t^{PRI} = PK_t^{PRI} \sum_{k,bus} IND_{k,bus,t}$$

$$PK_t^{PRI} = \frac{1}{A^{K\_PRI}} \prod_i \left[\frac{PC_{i,t}}{\gamma_i^{INVPRI}}\right]^{\gamma_i^{INVPRI}}$$

The allocation of new private capital between categories and industries follows a modified version of the Jung-Thorbecke (2001) investment demand specification. The volume of new type *k* capital allocated to business-sector industry *bus* is proportional to the existing stock of capital; and the proportion varies according to the ratio of the rental rate to the user cost of that capital, which may be interpreted as Tobin's *q*.

$$IND_{k,bus,t} = \emptyset_{k,bus} \left[\frac{R_{k,bus,t}}{U_{k,bus,t}}\right]^{\sigma_{k,bus}^{INV}} KD_{k,bus,t}$$

$$KD_{k,bus,t+1} = KD_{k,bus,t}(1 - \delta_{k,bus}) + IND_{k,bus,t}$$

With $U_{k,bus,t} = PK_t^{PRI}(\delta_{k,bus} + IR_t)$

The user cost of capital is defined in the usual way: it depends on the price of new capital (the replacement cost of capital), the rate of depreciation, and the rate of interest. In the present version of PEP-1-t, the rate of interest appears in no other equation. It is merely the rationing device that modulates investment demand in order to maintain total private investment expenditure within the constraint imposed by equilibrium condition. There are no actual payments in the model that depend on the interest rate. However, in a model with financial assets, the rate of interest would play a more elaborate role.

8.2. Variables that grow at a constant rate

Several constants and exogenous variables in the model are assumed to grow at the same rate nt as the population index pop_t. Labor supply is a variable that is assumed to grow at the same rate as the population index pop_t, as a result of population growth, or a shift in the participation rate, or a combination of both.

$$LS_{l,t+1} = LS_{l,t}(1 + n_t)$$

Other variables that grow at the population growth rate n_t are:

- ✓ The current account balance: $CAB_{t+1} = CAB_t(1 + n_t)$

- ✓ Minimum consumption of commodities in the LES demand equations: $C_{i,h,t+1}^{MIN} = C_{i,h,t}^{MIN}(1+n_t)$
- ✓ Government current expenditures: $G_{t+1} = G_t(1+n_t)$
- ✓ Public investment by category and by public sector industry: $IND_{k,pub,t+1} = IND_{k,pub,t}(1+n_t)$
- ✓ and, finally, changes in inventories: $VSTK_{i,t+1} = VSTK_{i,t}(1+n_t)$

The reason for assuming that constants and exogenous variables grow at the same rate as labor supply is to make it possible for the model to simulate a balanced growth path. An economy is said to follow a balanced growth path if all quantities grow at a constant rate, while relative prices remain constant. Of course, a balanced growth path is by no means a realistic scenario. But it may be useful as a « business-as-usual » (BAU) scenario, or to test model consistency. The balanced growth test can be considered to be the dynamic analog of the homogeneity test in static models, or the money-neutrality test in macroeconomic models.

9. Closures

In a Computable General Equilibrium (CGE) model, closures define the macroeconomic rules or assumptions that balance the system and ensure that the number of equations equals the number of unknowns. They specify which variables are endogenous (determined by the model) and which are exogenous (fixed from outside). In this context, the closures include the following key assumptions:

The nominal exchange rate is the numeraire, meaning it is used as the reference price and fixed to normalize the model's price system. This closure removes the indeterminacy in the absolute price level by anchoring all relative prices to the nominal exchange rate. Since the model operates in real terms, fixing the nominal exchange rate allows the real exchange rate to adjust through changes in domestic prices.

All tax rates are fixed, which implies that government tax policy is exogenously given and does not adjust in response to economic conditions. Therefore, the government budget balance must adjust through changes in other fiscal variables like transfers or savings. This closure assumes that the fiscal stance is maintained regardless of economic fluctuations, which is common in policy simulations aiming to isolate the effects of non-fiscal shocks.

Finally, the model assumes a small open economy, which means that the country is a price taker on international markets and cannot influence world prices. Hence, world prices are fixed and given exogenously. The domestic economy adjusts to changes in global markets through shifts in the trade balance, production, and consumption rather than through altering international prices. This closure is realistic for most developing countries with relatively small shares in global trade.

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