THE IMPACTS OF TRANSITING TO GREEN ENERGY IN AFRICA: EVIDENCE FROM GIS MAPPING AND SPATIAL PANEL MODELS

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by

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LIST OF ABBREVIATIONS

ACEC	African Clean Energy Council
AfDB	African Development Bank
ADF	Augmented Dickey Fuller
AIC	Akaike information criterion
AOI	Area of interest
ARDL	Autoregressive distributed lags
AREI	Africa Renewable Energy Initiatives
AU	African Union
BIC	Bayesian Information Criterion
BRICS	Brazil, Russia, India, China, and South Africa
CSP	Concentrated solar power
CO_2	Carbon dioxide emissions
DB	Database
DOLS	Dynamic ordinary least square
ECOWAS	Economic Community of West African States
EE	Energy efficiency
EG	Economic growth
EF	Ecological footprint
ELC	Electricity consumption
EI	Energy intensity
EIA	Energy Information Administration
EKC	Environmental Kuznets curve
FeM	Fixed effect model
FON	First order neighbors
FMOLS	Full modified ordinary least square
GDP	Gross domestic product
GE	Green energy
GES	Green energy source
GeoDa	Geographic Data Analysis
Gha	Global hectares
GI	Globalization index

GIS	Geographical information system
GDP	Gross domestic product
GMM	Generalized method of moments
GPP	Gross primary productivity
GTWR	Geographic temporal weight regression
Gt	Giga tons
GW	Gigawatt
HH	High-High cluster
HL	High-Low cluster
IEA	International Energy Agency
IEO	International Energy Outlook
IRENA	International Renewable Energy Agency
KG	Kilogram
Koe	Kilogram of crude oil equivalent
KWh	Kilowatt hour
LR	Long run
MLE	Maximum likelihood estimation
MW	Megawatt
MWh	Megawatt-hour
MCDM	Multi criteria decision making
NGES	Non-green energy source
NREC	Non-renewable energy source
OECD	Organization for Economic Cooperation and Development
ODA	Official Development Association
PET	Total primary energy
PCS	Projected coordinate system
PPP	Purchasing power parity
PRISMA	Preferred Reporting Items for Systematic Reviews
PV	Photovoltaic
QGIS	Quantum Geographic Information System
QML	Quasi-maximum likelihood
QR	Quantile regression
ReM	Random effect model
RE	Renewable energy

REC	Renewable energy consumption
REP	Renewable energy production
RES	Renewable energy source
SAA	Sub-Saharan Africa
SAR	Spatial autoregressive model
SD	Spatial dependency
SEA	Strategic environmental assessment
SEM	Spatial error model
SH	Spatial heterogeneity
SON	Second order neighbors
SLX	Spatial lag X model
SDM	Spatial Durbin model
SDG	Sustainable development goals
SR	Short run
SSA	Sub-Sahara Africa
TEC	Total energy consumption
LH	Low-High cluster
LISA	Local indicators of spatial association
LL	Low-Low cluster
LLR	Likelihood ratio
LRM	Linear regression model
TWh	Terawatt-hour
UK	United Kingdom
UN	United Nations
UR	Urbanization
USD	United States Dollar
USM	Universiti Sains Malaysia
UTM	Universal transverse mercator
VC	Variance-covariance matrix
VECM	Vector Error Correction Model
WEC	World Energy Council
WMO	World Meteorological Organization
WGS84	World Geodetic System 1984
POLSM	Pooled ordinary least squares model

LIST OF SYMBOLS

De	Direct effect
IDe	Indirect effect
Fe	Fixed effect
Re	Random effect
t	Time
X_i	Observation at polygon i
X_j	Observation at polygon j
β	Regression vector coefficient
f	Function
ε	Error term
$\boldsymbol{Y}$	Endogenous vector variable
$\boldsymbol{X}$	Exogenous matrix vector variable
$\boldsymbol{\alpha}$	Vector of scalar
$\boldsymbol{W}$	Weighted matrix
I	Moran's, I Statistics
I_k	Order k Moran's I value and $k = 1,2, \dots . N$.
H	Hypothesis
δ	Population standard deviation
H_0	Null hypothesis
H_1	Alternative hypothesis
ξ	Hausman statistic
ft	Feet
ln	Natural logarithm
ρ	Spatial autoregressive coefficient
λ	Spatial error coefficient

m	Meter
χ^2	Chi-square statistic
i	Observations
N	Number of objects
n	of object
θ	endogenous interaction coefficient
%	Percentage
$<$	Less than
P	Probability
R_w^2	R-square within
R_b^2	R-square between
R_o^2	R-square overall
^{0}C	Degree centigrade
S	Space
$\forall$	For each
ψ	Dynamic long run additive variable to ρ
η	Error term associated with Fe general spatial model
τ	Coefficient of lagged value of dependent variable

KESAN PERALIHAN KEPADA TENAGA HIJAU DI AFRIKA: BUKTI DARIPADA PEMETAAN GIS DAN MODEL PANEL RERUANG

ABSTRAK

Tesis ini mengkaji dinamik reruang terhadap pengeluaran dan penggunaan tenaga boleh diperbaharui (REP dan REC) dan kesannya terhadap pertumbuhan ekonomi (KDNK), jejak ekologi (EF), dan pelepasan karbon dioksida (CO_2) di 49 negara Afrika sepanjang tiga dekad (1990-2020). Kajian ini menggariskan keperluan peralihan kepada tenaga hijau yang mampan lanjutan daripada cabaran alam sekitar yang mendesak berkaitan dengan sumber tenaga konvensional (bahan api fosil). Objektif kajian adalah seperti berikut: (1) untuk menganalisis tren REP dan REC, (2) untuk meneroka autokorelasi reruang dan ciri-ciri dinamik data, (3) untuk menyiasat kesan REP dan REC terhadap pertumbuhan ekonomi dan kemerosotan alam sekitar, dan untuk mengenalpasti model reruang panel yang paling berkesan untuk dinamik ini. Untuk mengatasi isu anggaran dalam model bukan reruang konvensional yang gagal mengambilkira korelasi reruang dalam data, pemetaan GIS dan model panel reruang digunakan dalam kajian ini. Hasilnya dibandingkan dengan model bukan reruang. Pemetaan GIS menunjukkan bahawa jejak ekologi (EF) dan pelepasan CO_2 mengalami penurunan, terutamanya antara 2017 dan 2020, ini menunjukkan tren positif ke arah tenaga dan alam sekitar yang lebih hijau. Tambahan pula, kedua-dua REP dan REC menunjukkan pertumbuhan yang konsisten. Analisis autokorelasi reruang mendedahkan kewujudan autokorelasi reruang dalam data. Tambahan pula, pengaruh REC dan REP terhadap KDNK dan kualiti alam sekitar di Afrika telah disiasat menggunakan model regresi panel reruang. Mengurangkan pelepasan CO_2 dan jejak ekologi melalui REC mempunyai kelebihan alam sekitar jangka panjang dan

memberi kesan yang baik kepada KDNK. REP mempunyai kesan kecil ke atas EF dan kesan negatif jangka pendek ke atas KDNK disebabkan oleh kos peralihan awal yang tinggi.

THE IMPACTS OF TRANSITING TO GREEN ENERGY IN AFRICA: EVIDENCE FROM GIS MAPPING AND SPATIAL PANEL MODELS

ABSTRACT

This thesis examines the spatial dynamics of renewable energy production and consumption (REP and REC) and their impact on economic growth (GDP), ecological footprint (EF), and carbon dioxide emissions (CO_2) in 49 African countries over the course of three decades (1990-2020). The study underlines the necessity of a transition to sustainable green energy in light of the urgent environmental challenges associated with conventional energy sources (fossil fuel). The objectives are as follows: (1) to analyse the trends in REP and REC, (2) to explore the spatial autocorrelation and dynamic characteristics of data, (3) to investigate the impact of REP and REC on economic growth and environmental degradation, and to identify the most effective spatial panel model for these dynamics. To overcome the estimation issue in the conventional non-spatial model that fails to consider spatial correlation in the data, the GIS mapping and spatial panel models are utilised in this study. The results are compared with the non-spatial model. GIS mapping shows that EF and CO_2 emissions experienced a decline, particularly between 2017 and 2020, indicating a positive trend toward greener energy and environment while both REP and REC demonstrate consistent growth. The spatial autocorrelation analysis reveals the existence of spatial autocorrelation in the data. Furthermore, influence of REC and REP on GDP and environmental quality in Africa was investigated using spatial panel regression models. Reducing CO_2 emissions and EF through REC has long-term environmental advantages and favourably impacts GDP. REP has a minor impact on EF and a short run negative impact on GDP due to high initial transition costs.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Chapter 1 introduces Geographic Information Systems (GIS) and spatial modelling, introducing the study's main themes. It begins with a brief overview of spatial modelling, its characteristics, and its many applications in various fields, supported by relevant literature. The chapter, "The Impacts of Transiting to Green Energy in Africa: Evidence from GIS Mapping and Spatial Panel Models," emphasizes spatial modelling, GIS, green energy production and consumption, and carbon efficiency. Critical terms are defined to aid conception. In order to address regional issues, the chapter presents global statistics, research key variable trends, research questions, study objectives, and scope and significance. To aid comprehension, technical and fundamental terms from the study are defined.

1.2 Background of Study-Transition to GE and Environmental Issues

The 2030 Agenda for Sustainable Development emphasizes 17 SDGs, urging nations to protect the environment and human life. Clean energy (SDG7), sustainable production/consumption (SDG12), and economic growth (SDG8) are critical and interrelated. Policymakers must balance growth and environmental quality, as non-renewable energy use fuels production but harms ecosystems. Shifting to renewables is vital for sustainability.

Fossil fuels drive 75% of annual CO_2 emissions (36B metric tonnes), that worsening climate change. The World Meteorological Organization notes the last decade as the warmest on record, with a 1.5°C temperature rise likely by 2050 without action. Renewables energy (hydropower, solar, wind), but faster adoption is needed. Non-renewables (coal, oil, gas) are finite and polluting, while renewables (solar, wind, hydropower, biomass, and geothermal) offer sustainable alternatives (Dawood *et al.*, 2022; Frey & Linke, 2002; Moran, 2018; IEA, 2023). Renewables cut CO_2 emissions, improve air quality, and create jobs. Their infinite supply enhances energy security and scalability, especially in off-grid areas. Transitioning to renewables is the key to climate action and SDGs, fostering equitable growth while preserving ecosystems.

1.2.1 Energy Transition at Global Level

The global shift from fossil fuels to renewables is critical to cutting emissions and ensuring sustainability (Zhang *et al.*, 2024b). Though fossil fuels still dominate (80% of 2018 energy use), renewables (12–15% globally) are growing rapidly, especially solar/wind (over 20% in some regions). Europe leads this transition, with 40% of its electricity from renewables by 2022 Germany's share rose from 6% (2000) to 40% (2020) through policies like feed-in tariffs. The US reached 20% renewable electricity in 2022, lagging Europe due to weaker policy support (UN Statistics Division, 2021; World Bank, 2022). China, despite relying on coal, drove 40% of global renewable growth in 2021, with 28% renewable electricity by 2022. India aims for 50% by 2030. The Middle East and Africa face hurdles (funding, infrastructure), though the UAE and Saudi Arabia are investing in solar, while Ethiopia and Kenya use hydropower for 80% of their electricity.

Global renewable share rose from 5% (2000) to 20% (2020), aided by falling costs (solar: 90%; wind: 50%). The IEA forecasts that renewable energy will continue to grow, with renewables expected to account for 42% of global electricity generation by 2028. This growth revealed role of renewable energy in mitigating environmental degradation and supporting sustainable economic development. On the other hand, yet fossil fuels still supply 80% of energy (IEA, 2023). CO_2 emissions hit 38 gigatons in 2019; without faster transition, a projected 25% demand rise by 2040 will breach climate goals (IEA, 2020, 2022). Figure 1.1 illustrates this mix. Studies highlight renewables' role in carbon neutrality and energy security (Aldhshan *et al.*, 2021; Dong *et al.*, 2022). Non-renewables (coal, oil, uranium) drive climate change via emissions (Gernaat *et al.*, 2021). Post-COVID, steel/iron sector recovery could spike demand. China, India, and Japan will dominate future consumption (Figure 1.1), revealed the urgency of prioritizing green energy (Alvarado *et al.*, 2021).

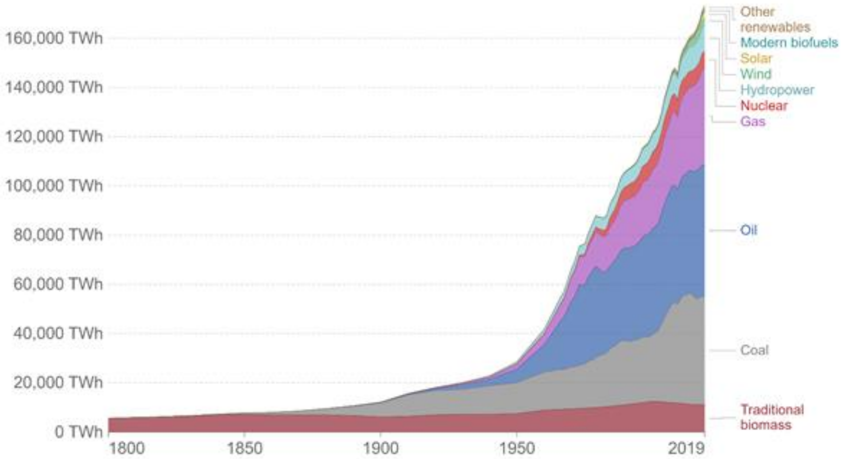

Figure 1.1 World Energy Consumption 1900 to 2019.
Source: Cantoni (2018)

Sustainable growth, energy security, and climate goals are way-out, since, fossil fuels still dominate (80% of primary energy; Zang *et al.*, 2021), but aligning with the Paris Agreement's 1.5°C target requires urgent action. The 2030 Agenda for Sustainable Development, adopted by 189 nations, prioritizes clean energy and pollution reduction (Alawneh *et al.*, 2019; Akuraju, 2020). Energy remains central to economic and social well-being, particularly in transport (Rackliffe, 2014). By 2040, non-OECD nations led by Asia will account for 64% of global demand (IEA, 2020b). Table 1.1 reveals a global decline in energy intensity (1990–2017), except in the

Middle East. CO_2 emissions reflect economic trends: rising in coal-dependent China and developing nations, but stable in the US (UNSD, 2021; World Bank, 2022).

Table 1.1 Energy intensity of GDP at constant PPP (koe/$2015)

Category	1990	2000	2010	2017
World	0.174	0.149	0.133	0.116
Europe	0.124	0.104	0.092	0.078
Asia	0.191	0.159	0.144	0.116
Africa	0.168	0.167	0.139	0.133
Middle East	0.101	0.117	0.133	0.131
North America	0.197	0.168	0.140	0.122
Latin America	0.167	0.145	0.123	0.111
CIS	0.328	0.333	0.221	0.202
Pacific	0.167	0.151	0.131	0.111

Source: Ahmad and Zhang (2020)

These trends show the need for cleaner energy to curb emissions. Table 1.2 projects global CO_2 emissions up to 2040, this highlighting the urgency of renewable adoption.

Table 1.2 Total CO_2 Emissions ($MtCO_2$) Projection

Category	2020	2030	2040
World	36265	38177	39549
Europe	3959	3313	2940
Asia	18444	21399	22738
Africa	1345	1780	2515
Middle East	2081	1887	1790
North America	5816	4793	4285
Latin America	1848	2028	2200
CIS	2363	2591	2720
Pacific	408	387	361

Source: Ahmad and Zhang (2020)

Table 1.2 projects rising global CO_2 emissions through 2040, driven largely by Asia, the CIS, Latin America, and Africa. Figures 1.2–1.4 detail historical trends (1990–2018) in global CO_2 from combustion, CO_2 intensity, and energy consumption, underscoring regional disparities and the need for mitigation.

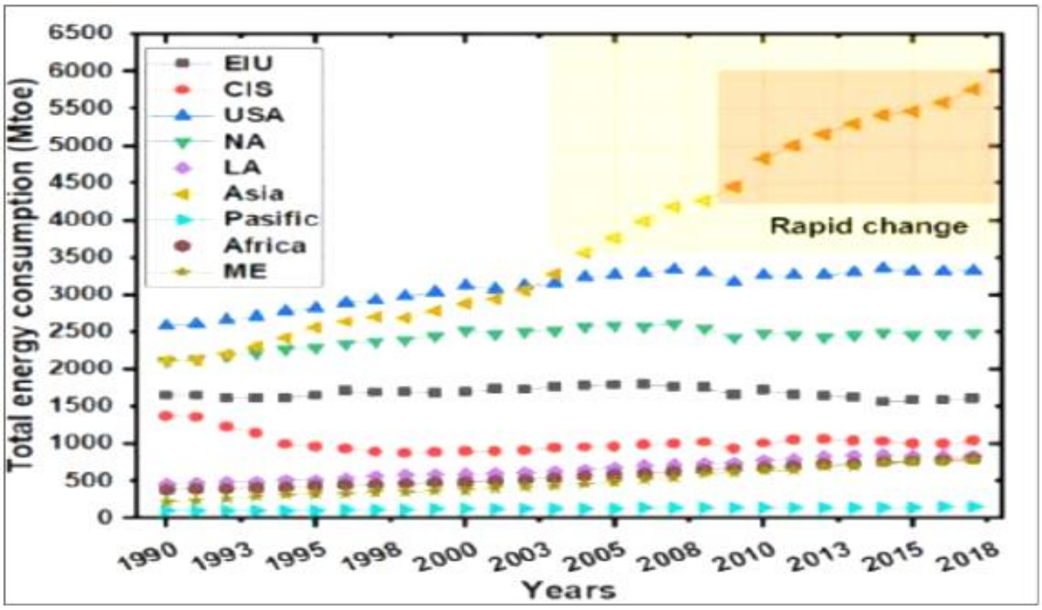

Figure 1.2 Energy Consumption 1990-2018
Source: Ahmad and Zhang (2020)

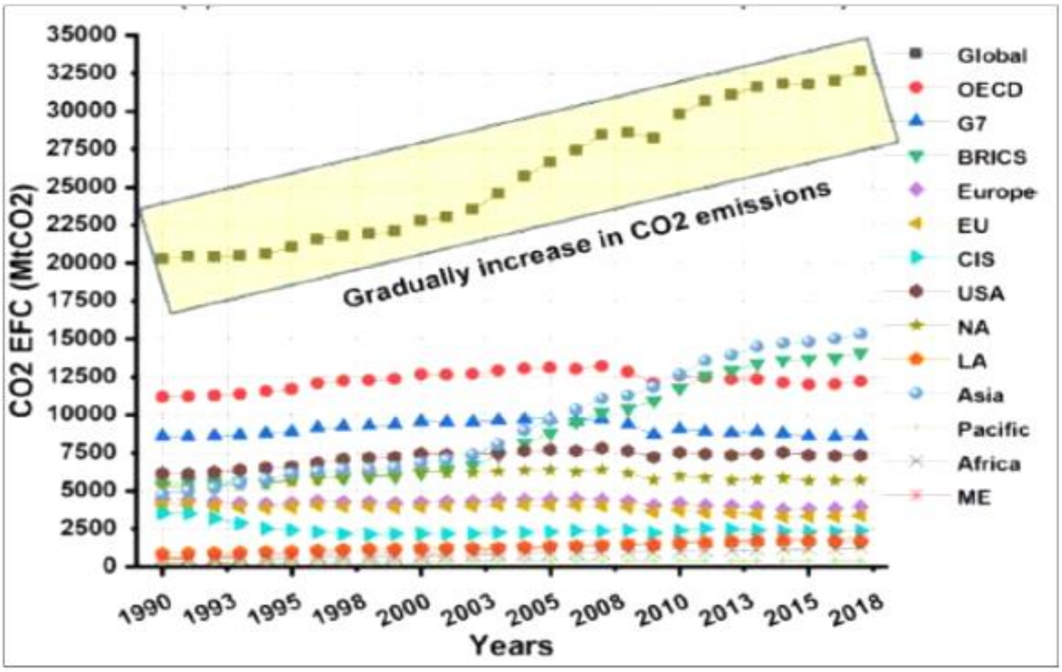

Figure 1.3 CO_2 from Fuel Combustion 1990-2018
Source: Ahmad and Zhang (2020)

Figure 1.2 shows yellow triangle shapes line represent Asia, which experienced rapid changed growth in total energy consumption between the period of 2003 to 2016 and Figure 1.3. The global total CO_2 emissions over the period 1990 to 2018 represented by square box orange colours line, the remaining regions can be observed from the figure's labels.

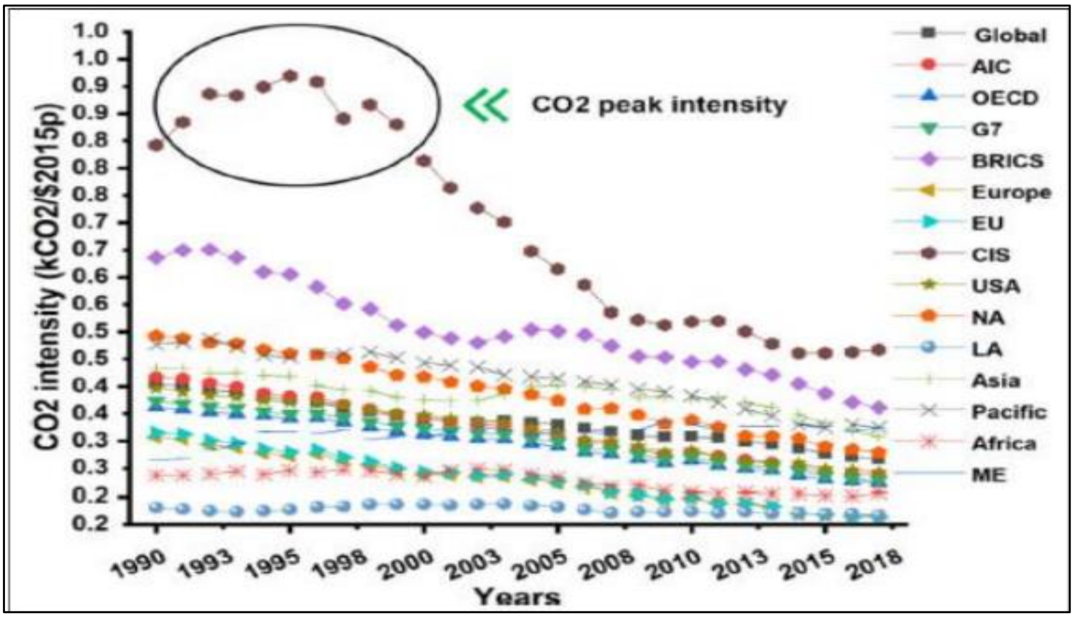

Figure 1.4 CO_2 Intensity At Constant PPP 1990-2018
Source: Ahmad and Zhang (2020)

Figure 1.4 shows a global decline in CO_2/GDP intensity since 1990. However, as Ahmad and Zhang (2020) note, emerging economies like China and India show rising intensity, contrasting with stable/declining trends in the EU and developed regions (Table 1.3).

Table 1.3 GDP CO_2 Intensity (kgCO_2/$15p)

Category	2020	2030	2040
World	0.267	0.197	0.144
Europe	0.158	0.109	0.080
Asia	0.316	0.223	0.152
Africa	0.199	0.170	0.149
Middle East	0.317	0.237	0.199
North America	0.268	0.185	0.138
Latin America	0.176	0.147	0.123
CIS	0.434	0.334	0.237
Pacific	0.268	0.188	0.130

Source: Ahmad and Zhang (2020)

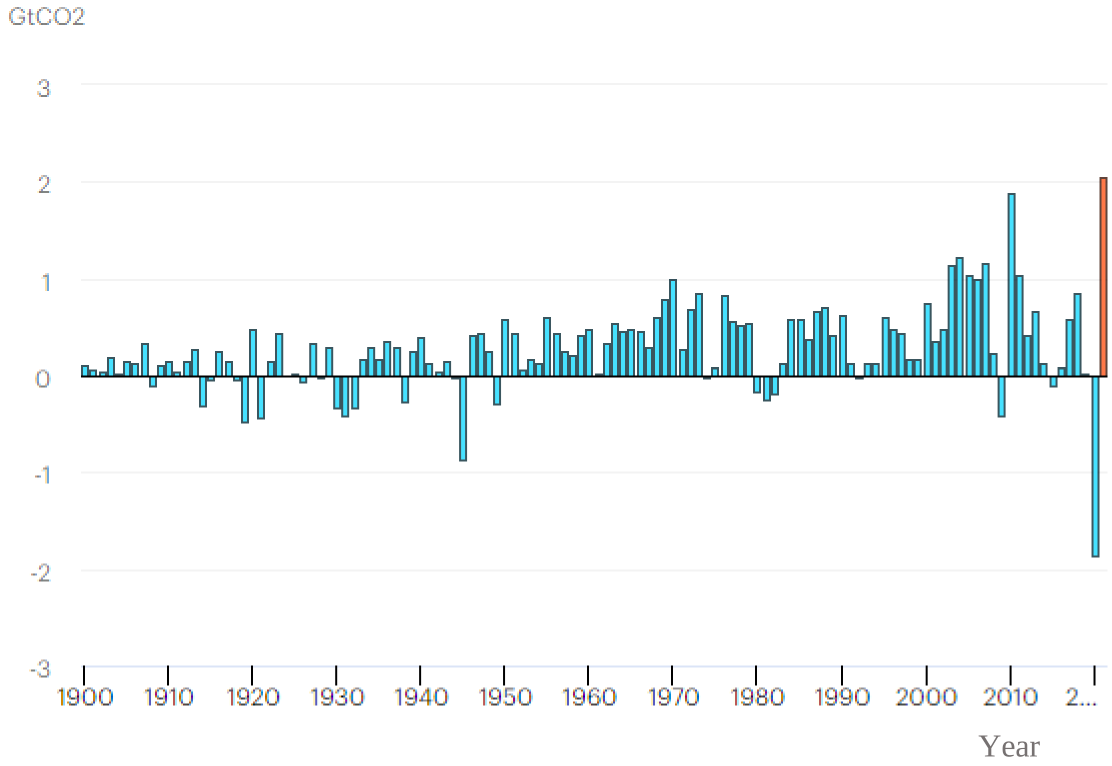

Figure 1.5 Fluctuations in Carbon Dioxide (CO_2) Emissions
Source: International Energy Agency (2021)

Figure 1.5 illustrates annual CO_2 emissions from energy combustion and industrial processes (1900–2021), with a record high of 36.3 Gt in 2021, a 6% increase from 2020 (International Energy Agency, 2021). The COVID-19 pandemic caused a 5.2% decline in energy demand in 2020, temporarily reducing emissions. However, economic recovery efforts, combined with adverse weather conditions and energy market disruptions, led to increased coal consumption in 2021 despite growth in renewables.

The shift toward affordable green particularly solar and wind, now among the most cost-effective energy sources offers significant economic benefits. Green energy generates more employment than fossil fuels while supporting sustainable development and climate mitigation.

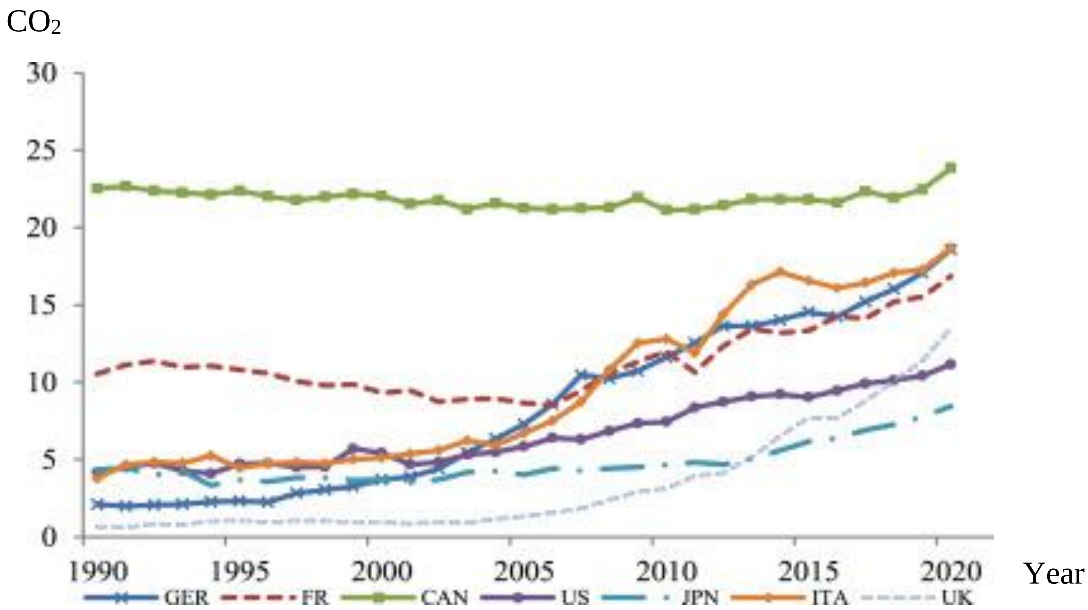

Figure 1.6 CO_2 Emission 1990-2020
Source: Zhang *et al.* (2024)

Figure 1.6 reveals significant regional disparities in CO_2 emission trajectories, with Africa's output projected to grow from 1,345 $MtCO_2$ (2020) to 2,515 $MtCO_2$ (2040), a faster rate than developed regions but slower than Asia's rapid increase, highlighting the urgent need for sustainable development strategies in emerging economies (UNSD & IEA, 2023). The global energy landscape shows a paradoxical trend: while renewables accounted for 30% of electricity generation in 2022 (led by hydropower, wind and solar), fossil fuels still dominate at 75% of total energy consumption (IEA, 2023). This transition has accelerated since 1990 when non-renewables comprised 90% of energy supply, with solar and wind capacity growing by 29% and 13% respectively in 2022 (IRENA, 2023). Regional variations remain pronounced, as evidenced by the EU generating 38% of its electricity from renewables compared to Asia's continued 55% coal dependence (UNSD & IEA, 2023).

The post-Paris Agreement era has seen uneven progress, with developed nations outpacing developing countries in renewable adoption (IRENA, 2023). Historically, energy systems have evolved through distinct phases from biomass and hydropower to coal (1800s), oil/gas (1900s), nuclear (1950s), and now renewables each transition driven by technological and economic factors (Hafner *et al.*, 2019). The current shift to renewables is particularly urgent due to climate imperatives and finite fossil reserves (Yi *et al.*, 2023; Ahmed, 2008), with Figure 1.7 (Statistical Review 2020) demonstrating renewable energy's critical role in achieving both SDGs and climate mitigation. While the inevitability of this transition is clear, its timeline remains the crucial variable, as delayed action risks exceeding critical climate thresholds (Büscher *et al.*, 2022).

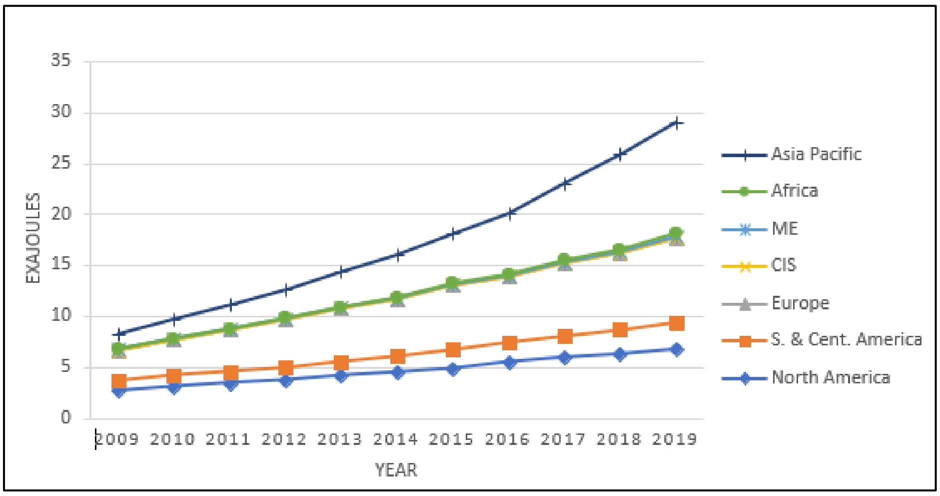

Figure 1.7 Green Energy Sources by Region
Source: BP (2021)

Green energy sources (GES), such as solar, wind, hydro, geothermal, sea waves, biomass, and biofuels, provide eco-friendly options that can aid in the reduction of carbon emissions, enhancement of air quality, and promotion of sustainable development in several sectors.

1.2.2 Energy Transition in Africa

As the world's second-largest continent spanning 34 million km² with 1.2 billion people, African diverse ecosystems and socioeconomic conditions make it a critical region for studying sustainable development (IEA, 2022). Despite possessing abundant renewable resources, Africa derived only 21% of its energy from renewables in 2021, with fossil fuels dominating at 79% (Africa Renewable Energy Initiative, 2021). However, investment trends show potential renewable energy capacity grew significantly with $6.5 billion invested in 2022 (AfDB, 2024), particularly in solar (5 GW capacity by 2020) and wind (3 GW capacity, 2,500 GW potential) (IRENA, 2018, 2020). Regional leaders demonstrate transition pathways including South Africa targets 30% renewable energy by 2030, while Kenya generates 40% from geothermal/wind (AfDB, 2019). Hydropower contributes 22% of continental capacity (28 GW), though environmental concerns limit expansion (IEA, 2020). Traditional biomass remains prevalent for heating and cooking (20% of primary energy), though modern applications are emerging (IEA, 2019). Globally renewables accounted for 27.2% of energy in 2020, with solar PV (fastest-growing) and wind leading capacity additions (UNSD, 2021). Cost reductions since 2010 (solar PV: 82%; wind: 39%) improve competitiveness (Centre for Climate and Energy Solutions, 2021). Figure 1.8 (IRENA, 2015) illustrates the evolving renewable balance, though technical challenges like intermittency persist (Abba *et al.*, 2022). Africa's transition exemplifies the complex interplay between resource potential, economic development, and climate imperatives.

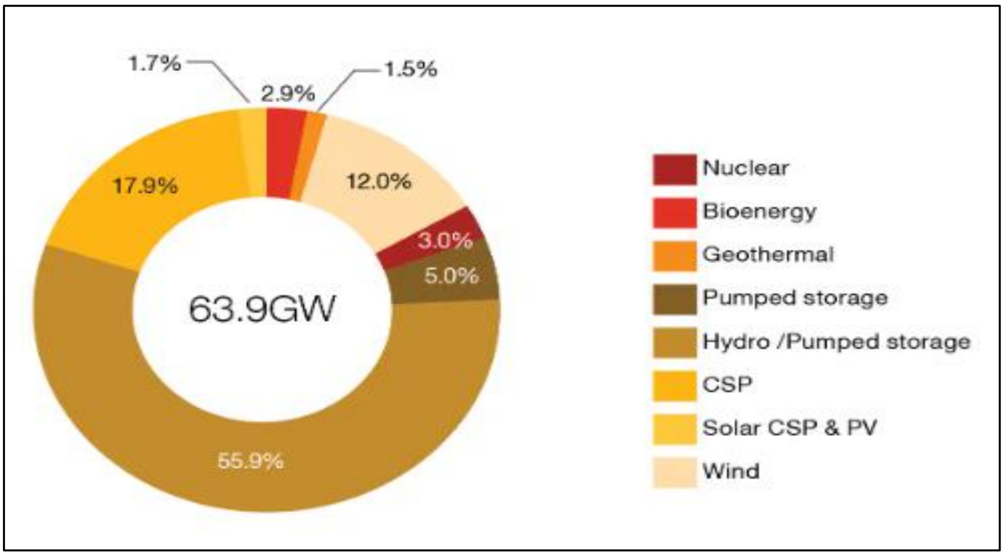

Figure 1.8 Renewable Energy in Africa
Source: African Energy Review (2023)

Figure 1.8 illustrates Africa's renewable energy capacity distribution, with hydropower dominating at 55.9%, followed by solar (17.9%), wind, and geothermal energy (IRENA & ILO, 2022). Despite this significant potential, the continent faces acute energy poverty, particularly in Sub-Saharan Africa where only 47.6% of the population has electricity access and approximately 600 million remain without power due to infrastructural deficits, high connection costs, and governance challenges. The renewable energy utilization gap remains pronounced, with only half of the 20% renewable-generated electricity being effectively deployed. Africa's energy systems remain heavily dependent on fossil fuels (70-90% in SSA), while biomass satisfies 69% of heating needs, creating a paradoxical situation given the continent's world-class renewable potential including solar irradiation capable of supporting over 5 GW capacity, 2,500 GW wind potential, and existing 28 GW hydropower capacity. Addressing these challenges requires focused interventions in three key areas: infrastructure modernization to integrate variable renewables and address the $6.5 billion annual investment gap (AfDB, 2024); innovative policy frameworks incorporating blended finance models and public-private partnerships; and technological leapfrogging through decentralized solar solutions and utility-scale projects. Figure 1.9's energy access data underscores the urgency for rethinking traditional grid paradigms through hybrid renewable systems, mini-grid deployment, and demand-responsive design to simultaneously expand access and decarbonize Africa's energy sector:

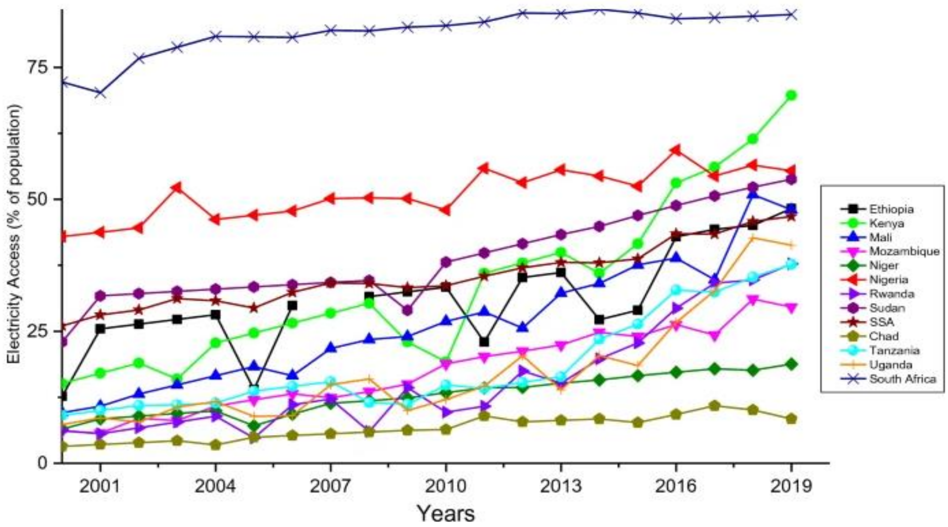

Figure 1.9 Energy Access for Some Selected Countries
Source: Mukhtar *et al.* (2023)

Hydropower remains African predominant renewable energy source, considering the continent's abundant river systems with average discharges of 17.7 m^3/s (Bugaje, 2006). Current installed capacity stands at 54 GW, projected to expand significantly through major projects like Ethiopia's 6 GW Grand Renaissance Dam - Africa's largest hydropower undertaking when completed (IEA *et al.*, 2021). Several nations derive over 50% of their electricity from hydropower, including Ethiopia, DRC, Zambia, and Mozambique, with untapped potential estimated at 1,753 GW continent-wide (Hoes, 2014). Major developments include Nigeria's 3,050 MW Mambilla project, Angola's 2,160 MW Cacula Cabasa facilities, and Mozambique's 1,500 MW Mphanda Nkuwa plant, positioning these countries as regional hydropower leaders. While fossil fuels still provide 74% of global energy due to historical cost advantages, renewables are becoming increasingly competitive. According to Walwyn and Brent, (2015) Africa's energy mix is consequently evolving, with hydropower leading the transition alongside growing wind and solar investments. Figure 1.10 illustrates this shifting balance between green and non-green energy sources across the continent, demonstrating hydropower's central role in Africa's renewable energy future while acknowledging the on-going importance of fossil fuels during this transitional phase.

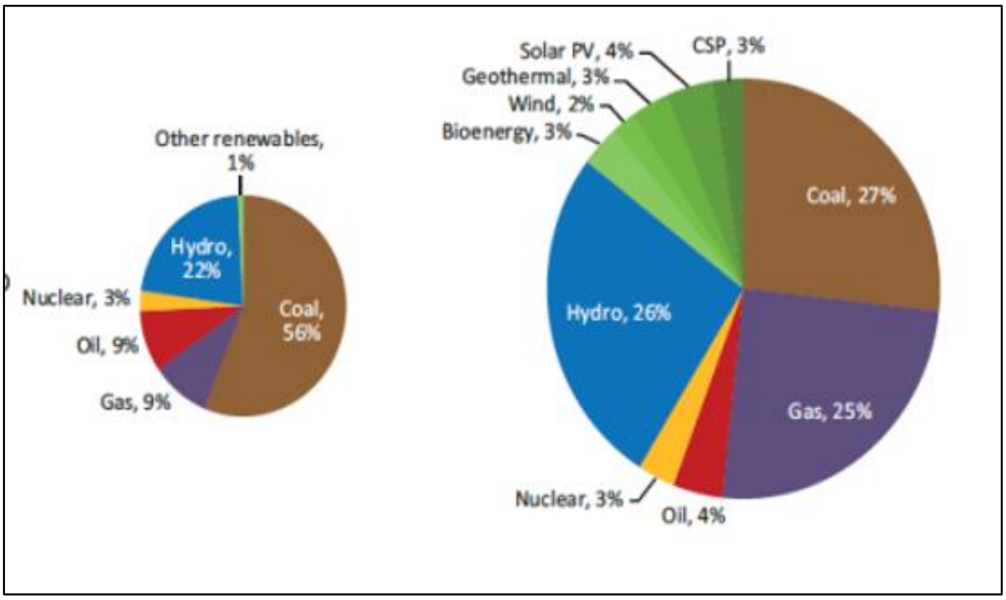

Figure 1.10 Green Energy Proportion 2012 and 2040
Source: IEA (2014)

Africa's renewable energy sector remains dominated by hydropower, though solar, wind, and geothermal show growing potential despite currently representing less than 3% of global renewable capacity (IRENA, 2022). The continent achieved 7% growth in renewable capacity from 2010-2020, primarily through large-scale hydropower and solar PV projects concentrated in Southern and North Africa, with South Africa contributing 17GW (one-third of continental capacity) and North Africa 12.6GW. Energy storage advancements and declining technology costs are facilitating this transition, though achieving universal electricity access by 2030 would require $389 billion in investments.

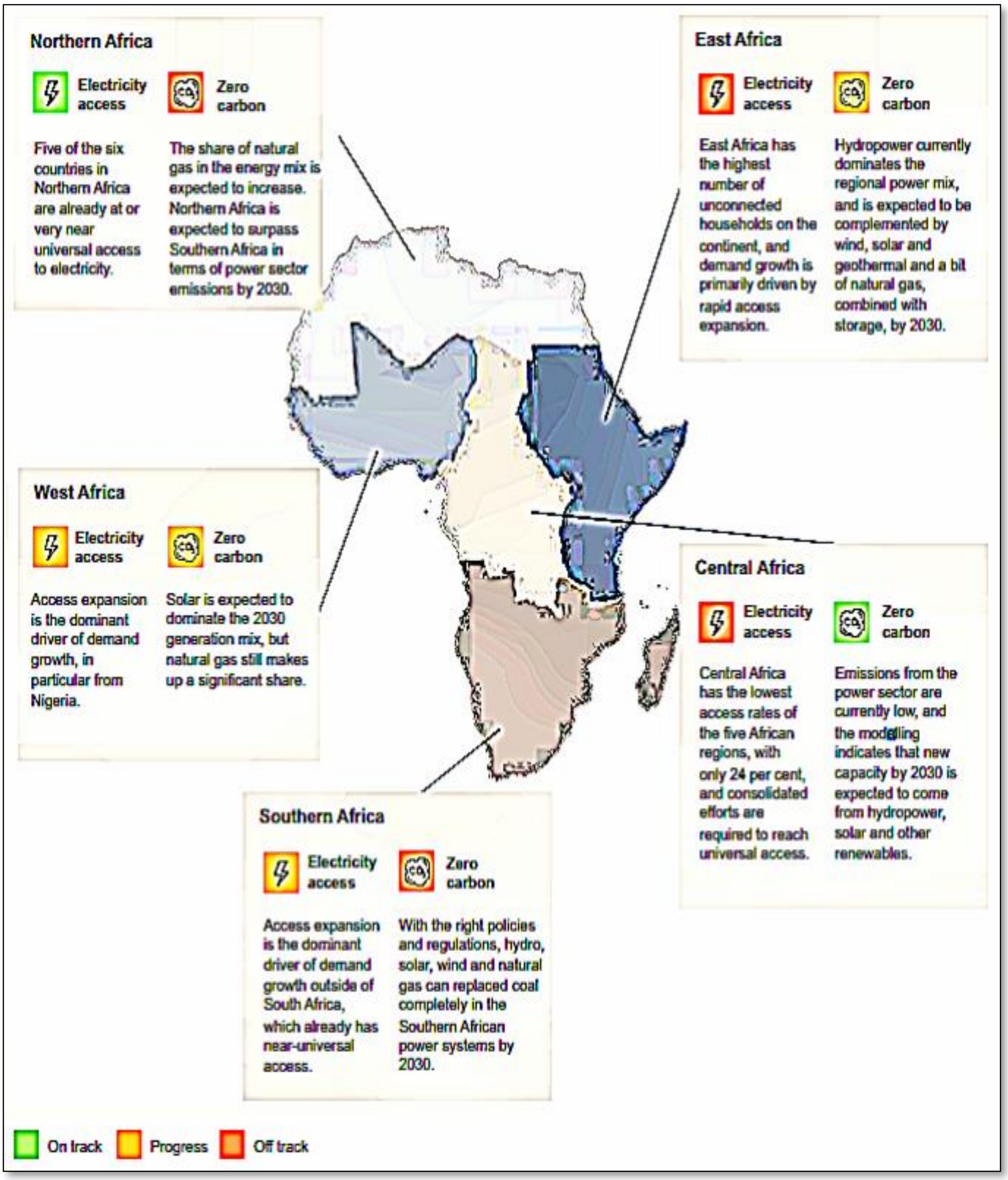

Figure 1.11 African Regions Evaluation Report on Zero Carbon and Access to Electricity
Source: IRENA, (2021b)

Regional progress varies significantly, with South Africa surpassing 10% renewable electricity penetration in 2022 through utility-scale projects, while Kenya derives 40% of its power from geothermal, hydro, and wind sources. Morocco's ambitious 52% renewable target by 2030 is supported by flagship projects like the Noor Ouarzazate Solar Complex, and Ethiopia maintains 90% renewable generation through hydropower, soon to be augmented by the Grand Renaissance Dam. Contrasting these leaders, Nigeria remains heavily dependent on fossil fuels despite growing off-grid solar adoption, while Ghana's renewable sector remains underdeveloped relative to its potential. Figure 1.11 above is a regional GIS classification ("On Track," "Progressing," "Off Track") and Table 1.4 below shows renewable potential assessment highlight these disparities, underscoring the critical role of policy frameworks and infrastructure investment in determining national energy transition trajectories (IEA, 2020a; World Bank, 2022).

Table 1.4 Theoretical Onshore Africa Green Energy Potential in TWh

Region	Hydropower	Wind	Solar PV	Geothermal	Biomass	Total
North Africa	56	334	348,782	101	64	448,025
West Africa	334	242,096	499,898	140,513	415	978,952
Central Africa	105	308,105	240,611	74,936	171,739	895,496
East Africa	642	154,916	171,739	246,212	96	740,125
Southern Africa	1,572	2,374	96	1,572	246,212	4,561

Source: IRENA (2021b)

Renewable energy adoption and decarbonisation progress, Morocco, Ethiopia, Namibia and Egypt demonstrate successful renewable integration, countries like Benin and Guinea face persistent challenges including infrastructure deficits, financing constraints, and limited utility access. The continent's continued heavy reliance on fossil fuels and low rural electrification rates (below 30% in many nations) underscore the urgent need for comprehensive policy reforms, infrastructure expansion, and international cooperation to enable a just energy transition. Africa possesses exceptional renewable energy potential that could fundamentally transform its energy landscape. However, realizing this green energy future requires addressing critical barriers including entrenched fossil fuel dependence, which currently contributes disproportionately to both local pollution and global climate change.

Table 1.5 Green Energy Transition in Africa

Country	Electricity Access	Renewable Energy Share	Key Renewable Projects	Challenges
Ethiopia	55% (low in rural areas)	Predominantly renewable, 98%	Grand Ethiopian Renaissance Dam (6,000 MW)	Inadequate infrastructure and financial resources for expansion
Ghana	82%	37% (hydropower-dominated)	Hydropower (Akosombo Dam)	Financial strain from overcapacity and reliance on fossil fuels
Morocco	High urban access	35% (solar and wind focus)	Noor Ouarzazate Solar Complex	Limited domestic fossil fuel resources, but strong renewable targets
South Africa	85%	11%	Renewable Energy Independent Power Producer Programme (REIPPP)	Heavy dependence on coal, aging infrastructure
Rwanda	65%	54%	Off-grid solar and hydropower initiatives	High electricity costs, especially in rural electrification efforts
Senegal	67%	Growing solar and wind share	158 MW wind project at Taiba N’Diaye	Challenges in rural electrification and grid reliability
Tunisia	99%	13%	Focus on solar and wind initiatives	Need for expanded infrastructure to support large-scale renewables
Benin	40%	Minimal renewable capacity	Small-scale solar projects	Low rural access, high fossil fuel dependency
Côte d'Ivoire	69%	30%	Azito Energy power plant (natural gas)	Hydropower potential, but limited renewable diversification
Egypt	Universal access	16%	Benban Solar Park	High reliance on fossil fuels, need for greater renewable diversification
Togo	50%	Low, emerging solar presence	Off-grid solar projects	Financial barriers, limited grid coverage in rural areas
Guinea	42%	40% (hydropower)	Hydropower projects (e.g., Kaleta Dam)	Limited grid infrastructure, high rural energy deficit

Source: IRENA (2021)

Table 1.5 (IRENA, 2021b) highlights significant disparities in African nations' The transition to renewable alternatives is not merely environmentally imperative but also economically strategic, given the finite nature of fossil fuel reserves and their volatile pricing. To capitalize on its abundant solar, wind, hydro, and geothermal resources, Africa must prioritize green energy source (GES) development through targeted investments, technology transfer, and capacity building, while establishing robust policy frameworks to accelerate deployment at both utility and distributed scales.

1.2.3 GIS and Spatial Modeling Analysis

This section establishes the theoretical foundation for employing geographic information systems (GIS) and spatial modelling in examining Africa's renewable energy transition. Spatial modelling has evolved into an indispensable analytical framework, integrating geospatial data with advanced econometric techniques to capture the complex spatial dimensions of energy systems (Anselin, 2010). The methodology addresses critical limitations of conventional analyses by explicitly accounting for two fundamental spatial characteristics: dependence (interdependencies between neighbouring locations) and heterogeneity (regional variations in relationships) (LeSage & Pace, 2009). Our application focuses on mapping renewable energy adoption patterns while evaluating their economic and environmental impacts across African regions.

The spatial modelling approach operates through an integrated workflow combining three components: geospatial data representation, statistical analysis of spatial relationships, and interactive visualization (Wang *et al.*, 2014). GIS platforms enable processing of multi-layered geographic data, from renewable resource potential to grid infrastructure and socioeconomic indicators (Resch *et al.*, 2014). This proves particularly valuable for energy transition analysis through three key applications: 1) identifying optimal locations for renewable projects based on resource availability and grid connectivity, 2) assessing spatial spillovers of energy policies across regions, and 3) visualizing transition pathways for stakeholder engagement (Martínez-Martínez *et al.*, 2022). The approach has demonstrated successful applications across African contexts, including renewable potential assessments (Quan *et al.*, 2015) and spatial econometric analyses of energy-GDP relationships (Bulavskaya & Reynès, 2018).

Modern spatial econometrics offers tools to address Africa's energy transition challenges. Our methodology adapts three principal model specifications: spatial panel models (SPMs) to capture neighbourhood effects in renewable adoption, geographically weighted regression (W) to identify location-specific relationships, and spatial panel models for longitudinal analysis of transition trajectories (Anselin, 2010). These techniques overcome the ecological fallacy inherent in conventional national-level analyses by recognizing that energy transition dynamics manifest differently across urban/rural divides, national borders, and resource-endowed regions. Recent applications demonstrate their effectiveness in optimizing renewable energy siting Saraswat *et al.*, (2021) and evaluating policy impacts (Shahnazi & Shabani, 2021) across heterogeneous African landscapes.

The research implements a four-stage analytical process: (1) compilation of geo-referenced datasets spanning energy, economic and environmental indicators; (2) spatial processing including hotspot analysis and suitability mapping; (3) econometric modelling of spatial relationships; and (4) development of interactive policy dashboards. This integrated approach yields three critical insights for Africa's transition: identification of high-potential renewable energy corridors, quantification of cross-border infrastructure benefits, and prioritization of regions requiring targeted interventions. The spatial perspective proves particularly crucial for addressing Africa's uneven energy access and renewable resource distribution, providing empirical foundations for decentralized energy solutions and regional cooperation frameworks. Subsequent sections detail model specifications and present empirical results across selected case studies.

1.3 Problem Statement

Africa faces a critical energy paradox, possessing abundant renewable resources yet struggling with widespread energy poverty. With 16% of the global population, the continent accounts for only 3% of world energy consumption, leaving over 600 million without electricity access (Hafner *et al.*, 2019). This disparity stems from systemic underutilization of solar, wind, hydro and biomass potential, compounded by inadequate spatial planning frameworks. Rapid urbanization exacerbates these challenges while increasing environmental degradation from persistent fossil fuel dependence.

The spatial dimensions of Africa's energy transition remain underexplored in conventional analyses. Critical spatial factors including cross-border energy interdependencies, geographic resource distribution, and regional access disparities significantly influence energy systems yet are frequently overlooked. Geographic Information Systems (GIS) and spatial econometrics offer transformative solutions by modelling these complex relationships (Vega & Elhorst, 2013). Spatial regression models effectively capture neighbourhood effects, while geographically weighted regression (W) accounts for regional variations in energy dynamics.

This research advances methodological approaches through spatial panel data analysis that addresses limitations of prior single-country studies. The framework incorporates nonlinear relationships and threshold effects, providing a more nuanced understanding of Africa's green energy landscape. Practical applications include optimal renewable energy siting, assessment of regional cooperation consumption and productions, and identification of targeted intervention areas. The spatial perspective yields actionable policy insights for decentralized solutions, cross-border electricity trade, and climate-resilient planning strategies.

The many of current researches on the relationship between renewable energy and the environment are based on conventional econometric models that fail to account for spatial dependencies. Visualising spatial patterns is restricted by the absence of dynamic spatial panel models and the limited use of GIS, particularly in African contexts. In addition, the Environmental Kuznets Curve (EKC) is the subject of mixed empirical evidence, with inconsistent results across regions and the majority of researches were conducted in developed countries. The number of studies that investigate the combined impact of renewable energy production (REP) and consumption (REC) on environmental quality and economic growth is limited. Despite its renewable energy potential, a substantial research gap exists in the assessment of the impacts of green energy across the continent, as no known studies have compared GIS and spatial panel approaches. This thesis aims to address this gap.

Key innovations include the integration of temporal and spatial dimensions in energy analysis, overcoming the ecological fallacy of Counties assessments. GIS visualization techniques enhance stakeholder understanding of green energy relationships, supporting evidence-based decision making. Subsequent analysis applies this framework to case studies across African regions, demonstrating its utility for guiding the continent's transition to sustainable green energy systems while addressing energy poverty and environmental challenges.

1.4 Research Questions

The research purpose is to provide insight into the on-going argument surrounding renewable energy in Africa, particularly using GIS and spatial data analysis methods and research seeks to fill gaps using GIS mapping and spatial panel models to analyse the impact of green energy in Africa. The primary research questions guiding this study are revised and streamlined as follows:

i. What is the green energy transition outlook in Africa?

ii. Is there spatial correlation in the data and what are the features characterize the data?

iii. How does green energy affect the African’s economy (economic growth and environmental quality) by considering spatial correlation? And determine which spatial panel models produce consistent results, and which method is most effective in accurately documenting the short-term and long-term effects across Africa?

These questions open an insight to examine Africa's renewable energy trends, patterns, effects on economic growth and environmental sustainability, and energy-related matters. To answer these questions, the research set an important and realistic objective.

1.5 Research Hypothesis

The research hypotheses that correspond to the aforementioned research questions are as follows:

H_1: There are significant upward trends and spatial disparities in the green energy transition in African countries from 1990 to 2020.

H_2: The adoption of green energy (consumption, production, and related economic and environmental variables) in Africa is characterized by spatial autocorrelation, with clustering patterns that are influenced neighbours.

H_3: The effects of green energy on economic growth and environmental quality in Africa are spatially variable; when analysed using an appropriately selected spatial panel model and spatial panel fixed effects models are the most effective in capturing these dynamics.

The research objectives of this study were to test the three core hypotheses mentioned above.

1.6 Objectives

The following objectives in subsections of this unit were set out to answer the research questions.

i. To examine trends for consumption and production of green energy in African over different three decades
ii. To explore the spatial correlation and dynamic characteristics of data
iii. To analyse the impacts of renewable energy (production versus consumption) in the economy of Africa by incorporating the spatial correlation through spatial panel models and determining the most suitable spatial panel models.

1.7 Scope and Methodology

This study employs geospatial analysis to examine Africa's renewable energy dynamics (1990–2020), focusing on consumption (REC), production (REP), carbon emissions (CO_2), GDP, globalization index (GI), and ecological footprint. The analysis is divided into two main parts as described in Figure 1.12 In the first part, GIS mapping and geospatial analysis are conducted to examine the changes in REP and REC over four decades cross-section data of Africa. The analysis is able to answer Objectives 1 and II. Next, the second part applies spatial panel models in estimating REP and REC equations based on panel data (1990-20202) for the region of Africa. This will answer the third objective.

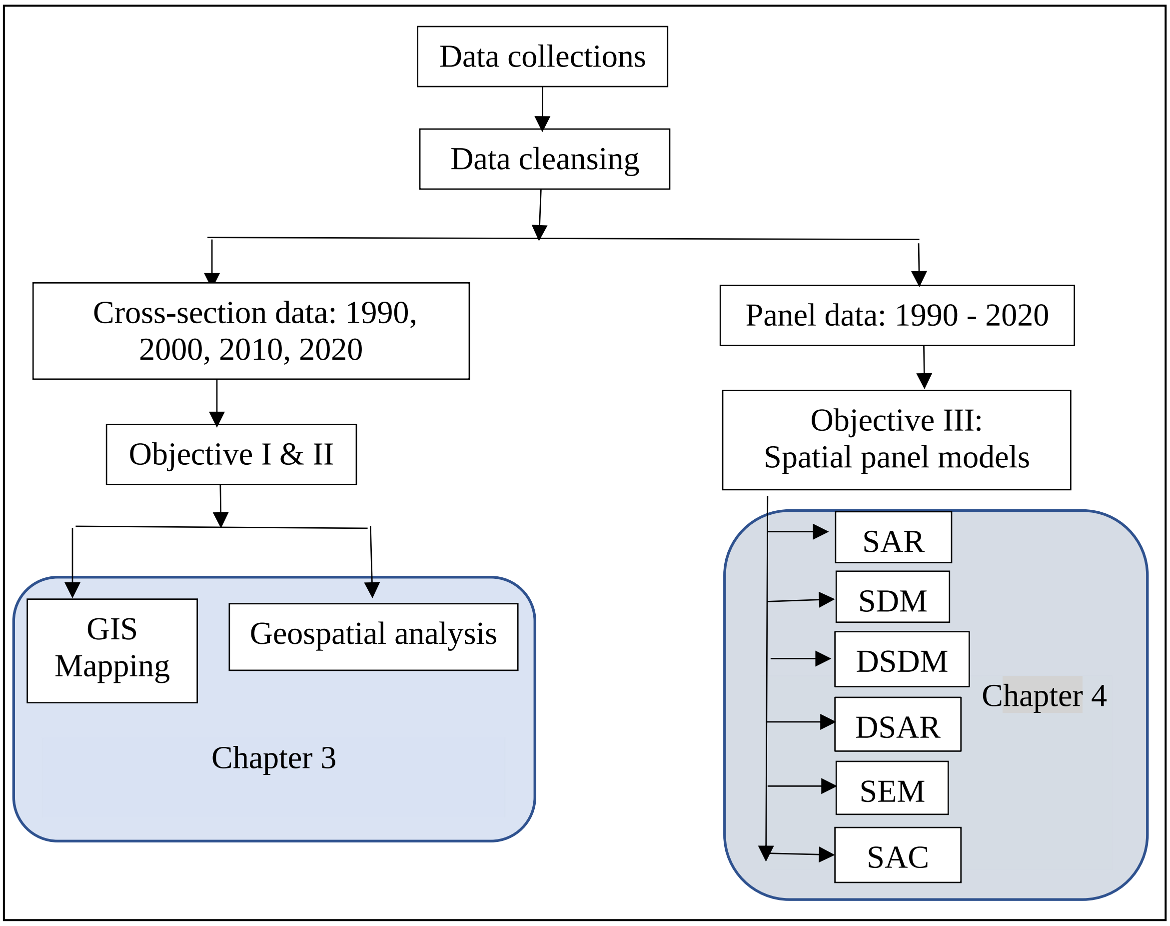

Figure 1.12 The Structure of Analysis

Chapters 3 and 4 elaborate on this research methodology that involved model specifications, diagnostics, GIS mappings and spatial clustering techniques and special panel models effects in revealing hidden insight to shaping green energy strategies across Africa.

1.8 Significance and Contribution of the Study

This study contributes to the green energy (GE) literature in two key areas: theoretical and empirical advancement, and socio-economic impact. It builds upon existing frameworks to evaluate the effects of renewable energy on both consumption and production, addressing a significant gap in prior research which largely focused on consumption alone. By comparing renewable energy production (REP) and consumption (REC), this research offers deeper insights into their respective economic implications. The major contribution lies in uncovering spatial correlations across data from 49 African countries, which earlier studies overlooked. By incorporating spatial effects through GIS mapping and dynamic spatial panel models including the Spatial Autoregressive Model (SAR), the Spatial Autocorrelation Model (SAC) and Dynamic Spatial Durbin Model (DSDM) etc. that aided in captures of short and long-run, direct and indirect effects, offering more accurate estimations.

This study makes a substantial contribution by addressing the lack of consensus regarding the role of green energy in economic growth and environmental quality, particularly in Africa. It integrates renewable energy production (REP) and consumption (REC) to investigate their combined effects using an evidence-based approach. The research employs dynamic spatial panel models (e.g., Spatial Durbin and Spatial Autoregressive Models) and GIS mapping to identify spatial dependencies, spillover effects, and long-term trends. It provides region-specific insights into sustainable development and green energy transitions by concentrating on African countries. This work not only resolves theoretical disagreements but also offers new empirical evidence and practical guidance for policymakers by conducting a spatially detailed analysis of energy, environment, and economic interactions across the continent.