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Energy transition of African countries: Dynamics, Policy Implications and Pathways to Sustainable Development

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Introduction

Energy is the greatest discovery humanity has ever been able to reach. It is the main purpose for the progress of our current world through its machines, devices, technologies and vehicles. Energy sources have existed on the earth for a long time ago, even before the existence of humans. One of the first energies ever is the sun. Sun has lighted and has heated our planet since early times. Then, it was used by primitive humans as the first energy that offered heat. Our first ancestors had used basic energy to survive but the discovery of energy transformation was the turning point in the history of the human species. That is why energy history is divided into eras based on energy conversion and the tools and materials used to convert. During prehistory, early humans' activities were based on their somatic energy using their muscles to cook and build shelters. Many years after, they discovered fire and it facilitated more of their basic activities ([Smil \(2004\)](#)).

Fire represented the first extra somatic energy in early times until the domestication of animals. The strength of draft animals, which offered the first mechanical energy, has been widely used for agricultural purposes. Cows, bulls, horses and mules represented for ancient civilizations a significant source to plow fields, pull carts and transport goods and even people ([Smil \(2004\)](#)).

The use of fire and draft animals constituted the first great energy transition and together they paved the way for the second era of transition characterised by the reliance on the prime movers: water and wind wheels and sailboats. The first wheels invented by humans in the first century BCEa were those working with flowing water. Wind wheels are the second type of wheels and they appeared one thousand years after the water-driven wheels. Both types of wheels were employed to press oil, grind grain, pump water, irrigate, saw wood, full minerals, transportation and other activities ([Viollet \(2017\)](#); [Allamehzadeh \(2016\)](#)). Principally, the second era of energy was determined by the dominance of the mechanical energy that enabled the wheels to move and operate. After Millennia, new innovations have seen the light and have shifted the world to a new era where biomass was replaced by fossil fuels and the prime movers by engines ([Smil \(2004\)](#)).

The third era of energy, which represents the second great energy transition, started after making use of the first fossil fuel source, coal. Coal represented the foundation stone of the Industrial Revolution and its importance was highlighted when it was used to power the steam engine in 1760. Together, the steam engine and coal changed societies and gave rise to other important innovations such as locomotives, steam-powered vessels ([Kander and Stern \(2014\)](#)). Around the same period, two other fossil fuels natural gas and oil were discovered. Oil and natural gas have contributed to further technological advancement and were used as main energy sources for heating, manufacturing, and particularly trans-

portation and automobile sectors. Oil, also played a relevant role in determining several historical events such as the First World War. Energy in general has been considered one of the decided factors in wars, since the early centuries with the use of arms and metals until Second War II with the use of nuclear, which saw the light in the early 20th century ([Smil \(2004\)](#)).

Therefore, energy is recognised as the first basis for progress and has become an integral part of our daily lives. In particular, fossil energy has played a significant role in this progress, enhancing human development, providing electricity, empowering economic sectors and boosting economic growth ([Wu and Chen \(2017\)](#)). At the same time, this increasing use of fossil has generated strong damage. As commonly understood, fossil energy is directly related to CO₂ emissions which contribute to climate change and global warming, threatening the planet and human life. The increased atmosphere temperature has strongly increased natural disasters and affected the ecosystems, biodiversity and human well-being. Global warming caused the melting of glaciers and ice caps, which added more water to the sea and raised its levels ([Shivanna \(2022\)](#)). CO₂ emissions have negatively affected the quality of the air and increased pollution, leading to significant risks to human health ([Yirong \(2022\)](#)). In addition to their environmental threats, fossil fuels are strongly associated with price fluctuations and geopolitical tensions ([Scholten et al. \(2020\)](#)). During the last decades, fuel prices have seen inherent volatility, particularly during times of crisis such as the global financial crisis and the Russian–Ukraine war ([Tumala et al. \(2023\)](#)). The Russian–Ukraine war and tensions between Russia and Western countries are also recent examples of fossil fuels and their association with energy conflicts.

Due to these serious impacts, global efforts were focused on reducing global fossil use and enhancing the energy transition towards renewable energy, and that is what represents the new energy era or the new energy revolution.

Renewable energy, unlike fossil fuels, is away from any dimension of energy security risks. First, renewable sources such as solar, wind, hydropower and bio-energies are abundant and repetitively formed in nature and are also available for each region ([Khan et al. \(2023\)](#)). Accordingly, renewables can provide long-term sustainability for each country and thus, it may also reduce geopolitical tensions, mainly related to fossil energy use ([Agaton \(2022\)](#)). In addition, the fact that this energy is domestically produced, countries that strongly rely on fossil imports will see their production increase and their energy imports decrease, and they will achieve greater independence and self-sufficiency in terms of energy ([Soukiazis et al. \(2019\)](#)).

Regarding the economic challenges, compared to fossil fuels, clean energy can offer more stability for national and global economies. Renewable energy generation leads to a decrease in energy prices contrary to fossil fuels, which are highly associated with price

variability ([Tumala et al. \(2023\)](#)). Moreover, renewable technologies offer environmental sustainability since they are environmentally friendly with less negative impacts, while fossil energy has long been the main contributor to climate change through the release of CO₂ emissions after its burning ([Bilgili et al. \(2016\)](#); [Le et al. \(2020\)](#)).

Consequently, international organisations along with governments in different countries around the world have emphasised the necessity of adopting efficient RE policy reforms in each country's national plan and shifting their energy system towards renewables. Furthermore, a wide number of international agreements and initiatives have taken place as a form of global and collaborative actions to mitigate climate change and enhance energy security such as the United Nations Convention on Climate Change in 1992, the Kyoto Protocol in 1998, the Paris agreement in 2015, the European Green Deal in 2019 and Net-Zero Targets in 2019 ([Baye et al. \(2021\)](#)). As a consequence, RE generation and consumption have seen a significant improvement, especially in the last decade.

According to British Petroleum statistics, the global primary energy consumption has continued to increase reaching in 2021 the largest growth in history with 595.15 EJ. This increase was entirely explained by the expansion of RE sources which represented 17.7% of total final energy consumption in 2019. In 2021, the global RE consumption reached 39.91 EJ and it was mainly driven by solar and wind energies which accounted together for more than half of total RE consumption in the last 10 years ([Li et al. \(2022\)](#)).

Nevertheless, the development of RE remains uneven across regions and countries. Among all the regions, Asia Pacific outpaces the rest of the regions in RE installed capacity and includes the largest amount of RE. According to British Petroleum, almost half of the RE consumed in the world was registered in this region, accounting for 17.5 EJ in 2021. This large amount was mainly due to China's contribution which represents more than 60% of total RE consumed in Asia and 28.4% of the amount consumed worldwide, making it the largest renewables generator and consumer in the world ([BP \(2022\)](#)). Following Asia, Europe is the second largest region in terms of RE generation and consumption, which accounted for 25.9% and 25.4% of global renewables in 2021, respectively. North America and South and Central America by their turns represent 21.2% and 8.4% of worldwide RE, respectively, with the United States being the largest consumer and generator of renewables in North America (18.7%) and Brazil leading South and Central America (6%). As for Africa, with only 1.3% of global RE generation and 1.2% of global consumption, it is still far behind compared to different regions of the globe ([BP \(2022\)](#)).

Paradoxically, Africa has a great potential for renewable sources starting from rivers and water channels for hydropower, abundant sunlight for solar energy to a large wind power potential. Regardless of this vast potential, only a small part of it could be tapped in the continent due to several factors such as financial barriers, poor infrastructure, limited

access to advanced technologies, weak institutional framework and inadequate policies. Therefore, by harnessing its capacity, Africa still has too much to offer in terms of RE, and its contribution to the international RE sector is fundamental for the acceleration of RE development, and also beneficial for the continent's development ([Ouedraogo \(2019\)](#)). In particular, the RE increase will represent a tremendous opportunity for the continent to establish a low-carbon system and thus mitigate climate change, satisfy its growing energy demand driven by its accelerated population growth, and improve its low standard of living due to the fact that Africa is home to the largest number worldwide of people living without access to stable and reliable energy supply ([Baye et al. \(2021\)](#)).

Therefore, RE is a key element for achieving effective sustainable energy and sustainable development, and every African country, individually and collectively, should build a suitable framework to promote its deployment. African countries differ from each other in terms of their economic and political situation, natural resources, renewable potentials, and regulatory and policy frameworks, resulting in different RE developments and a heterogeneous African RE scene.

This thesis examines the energy landscape in Africa and focuses on renewable energy development and its interaction with the mentioned concepts. Africa represents a critical focus for energy transition studies. First, the focus on Africa in the previous studies has received less attention compared to other regions, which results in weak policies and strategies for the development of the energy system of the continent. Moreover, analysing the African energy transition allows for better design of energy policy, affecting the economic and social development of many Africans who still lack energy access, and suffer poverty and inadequate infrastructure. Lastly, Africa's abundant natural resources make it play a key factor in the global transition toward RE. Its unharnessed energy resources offer great opportunities to enhance energy access across African countries, support neighbouring regions and create new commercial ties with other countries.

The first objective of the thesis is to study the energy dynamics of some African countries, which countries have similar or different trends in terms of renewable and fossil energy and what factors can influence the energy structure in these countries. In the first chapter of the thesis, the first research questions were developed and some policy implications were presented in relation to Sustainable Development Goals (SDGs).

The second chapter focuses on SDG number 7: "Ensure access to affordable, reliable, sustainable and modern energy for all". In specific, it investigates the relationship between renewable energy development and energy security in African countries. Not only that but it also takes into account the interaction between energy security and other energy and economic variables. The results of the empirical work were compared with other countries outside Africa, including developing and developed countries.

The last chapter of the thesis goes deeper and focuses on one aspect of energy security. For African countries that witness increasing population growth and lack accessibility to electricity, energy security represents the ability to ensure energy supply and reduce energy poverty. This chapter studies energy poverty in Africa and how it can be influenced by other socioeconomic factors, in particular, Chinese Foreign Direct Investment (FDI). This chapter was developed during my visiting period at the Nanjing University of Science and Technology.

It is worth mentioning that some analyses of the three chapters have been published (see Appendix .1 for more details) and some are still under review.

Chapter 1

The energy transition of African countries: a cluster analysis

This Chapter tries to answer the first research questions and reports the results of the first published paper ¹ (see Appendix .1 for the published paper). The analysis tries to give a deep and comprehensive understanding of the energy landscape in Africa over time and by country in order to identify general trends. The aim is to elaborate an interpretative scheme to understand different choices of RE investments based on the structural dynamics in the energy markets and on political and socio-economic variables.

In order to analyse the key points, the study will make use of Ward's method for cluster analysis in 25 African countries over the period 2000-2020 using 5 variables on energy namely RE consumption, RE production, fossil fuels consumption, fossil fuels production and fossil fuels imports, in addition to the other economic, social, political and environmental factors to explain RE diffusion in the African continent namely GDP per capita, Foreign Direct Investment, trade openness, Human Development Indicator, Political stability, level of democracy, World Economic and Social Impact Index and CO2 emissions.

This chapter is organised as follows, the next paragraph will include an overview of RE's potential and status in Africa. The second section will present the literature review on the determinants of RE. In the third section, the data and the methodology utilised are introduced. Lastly, the last two sections will discuss the results obtained and give brief conclusions.

¹Emna Kanzari, Gioacchino Fazio, Stefano Fricano (2024). "Analysing the energy landscape in Africa using cluster analysis: Drivers of renewable energy development". *Energy Policy*, 2024, 195: 114366. Presented at AISRe, XLIV Annual Scientific Conference.

1.1 The state of the art of renewable energy in Africa: Potential and recent trends

1.1.1 Renewable energy sources potential in Africa

Africa holds plenty of natural resources which makes it one of the richest continents in the world in terms of natural sources including solar, wind, hydro and bio energies. Regardless of this abundance, the continent could harness only a small fraction of its total high and diversified potential including solar and hydro in most of the countries, wind in the coastline and geothermal in East Africa ([Olanrewaju et al., 2019](#)).

Many studies in the area of RE in Africa have been conducted to discuss the continent's potential in terms of renewables and the gap between this potential and the present installed capacity.

According to [Hafner et al. \(2018\)](#), Africa is situated within latitudes 37°N and 32°S covering a vast part of the earth that crosses the equator and the tropics. The continent's location makes it one of the continents with high average temperatures and the highest potential for solar power in the world. Over 80% of the continent receives solar irradiation of about 2000 kWh per square meter yearly, accounting for an average of 5 kWh per square meter per day as specified in Figure 1.1. Nevertheless, according to the International Renewable Energy Agency (IRENA), the total installed capacity of solar energy in Africa represents only 1.2% of the global installed capacity, accounting for 12641 MW in 2022. While solar Photovoltaic PV represented around 1% of the world's installed capacity of PV, solar thermal's share was about 17% of global solar thermal in 2022. For instance, as mentioned by [Adenle \(2020\)](#), South Africa's potential for solar PV accounts for 42243 TWh per year and its concentrating solar power is 43275 TWh per year. Kenya's solar PV is 23046 TWh per year and its concentrating solar power is equivalent to 15399 TWh per year.

By and large, solar energy in Africa is fairly distributed across the continent, unlike wind energy potential. Wind power is mainly determined by its speed which is related to pressure gradients and the landscape shape and thus, high wind speeds can be found in deserts, coastlines and natural channels. For Africa, the highest potential of wind can be registered in all countries of the Sahara and Sahel regions for example, Sudan and Niger, all coastal countries, mountainous regions in Southern Africa such as South Africa and Zambia and finally in the Horn of Africa and Rift Valley including for instance Ethiopia, Tanzania and Kenya ([Hafner et al., 2018](#)). As reported by IRENA, the total theoretical wind power potential in the continent is estimated to be around 457665 TWh/year and only a few of it was able to be harnessed. The total installed capacity accounted in 2022 for 7685 MW, equivalent to 0,85% of the global installed capacity of the wind. The largest African

markets of wind power are South Africa, Egypt, Morocco, and Kenya with a total installed capacity in 2022 of 3103 MW, 1643 MW, 1556 MW and 436 MW, respectively.

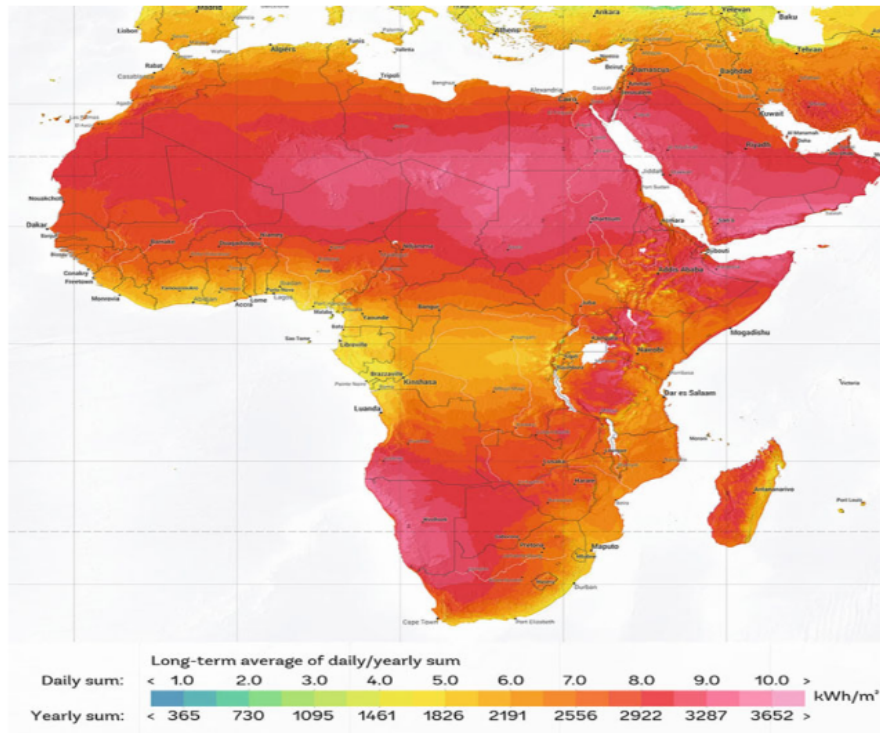
Similar to solar and wind, hydro energy also has a great potential which is equal to 1750 TWh and most of it is mainly concentrated in the sub-Saharan region that includes plentiful rivers such as Congo, Niger, Nile, Orange, Senegal and Volta. The African countries with significant hydro capacity are Senegal, Cameroon, Ethiopia, Madagascar, Nigeria, Mozambique and Guinea but the highest potential is unquestionably found in the Democratic Republic of Congo which alone accounts for 50% of the total potential. Same as the other renewables, there is an important lag between this potential and the installed hydropower capacity in Africa and only about 5% has been utilised ([Hafner et al. \(2018\)](#); [Olanrewaju et al. \(2019\)](#)). According to IRENA, hydropower energy is the most diffused RE source in Africa and it has been used more than solar and wind energies together. In 2022, the hydro installed capacity was 38851 MW with Ethiopia, Angola, Zambia, Egypt, Congo DR and South Africa being the countries with the highest installed capacity with 4821 MW, 3729 MW, 3164 MW, 2832 MW, 2719 MW and 3484 MW, respectively. Geothermal energy is spread extensively throughout the continent and it is easily reached particularly close to volcanoes, geologic rifts and hot springs. As reported by [Hafner et al. \(2018\)](#), in the same study, geothermal potential stands for 15 GW mainly concentrated in East African countries such as Tanzania, Eritrea, Kenya and Uganda but only 6% of it has been tapped, accounting for 0.95 GW in 2022. Almost all of this installed capacity is centralised in Kenya with 949 MW according to IRENA statistics.

The last two forms of RE with high potential in Africa are bioenergy and hydrogen. Bioenergy is based on the exploitation of wood and waste and the continent is known for having significant forest areas, mainly concentrated in Central and West Africa. As stated by Africa Energy Outlook 2022, the surplus forest is expected to produce 520 GWh per year of wood supply and the agriculture residues are able to provide more than 100Mt yearly to generate electricity and biofuels. The installed capacity of bioenergy in the continent was about 1847 MW in 2022 out of which 335 MW in Ethiopia and 295 MW in South Africa. Hydrogen potential is advantageous as well and the continent has the largest capacity worldwide to generate hydrogen from low-cost renewable electricity. It is estimated that the continent is able to offer 5000 megatonnes of hydrogen/year, which is equal to the current global energy supply, at less than 2\$ per kilogram ([IEA, 2022](#)).

Renewable potential is immensely high in the African continent as previously explained but also its important minerals potential plays a key role in energy transition as they can be used to produce RE technologies such as solar and wind turbines. As an example, the biggest producer of cobalt in the world is the DR of Congo with 2/3 of the world's cobalt production and 70% of the global platinum is generated in South Africa ([IEA, 2022](#)).

RE in Africa will have a promising future if it is well exploited, fairly diffused and enhanced by efficient policies.

Figure 1.1: Solar energy potential



Source: Global Solar Atlas, owned by the World Bank Group and provided by Solargis.

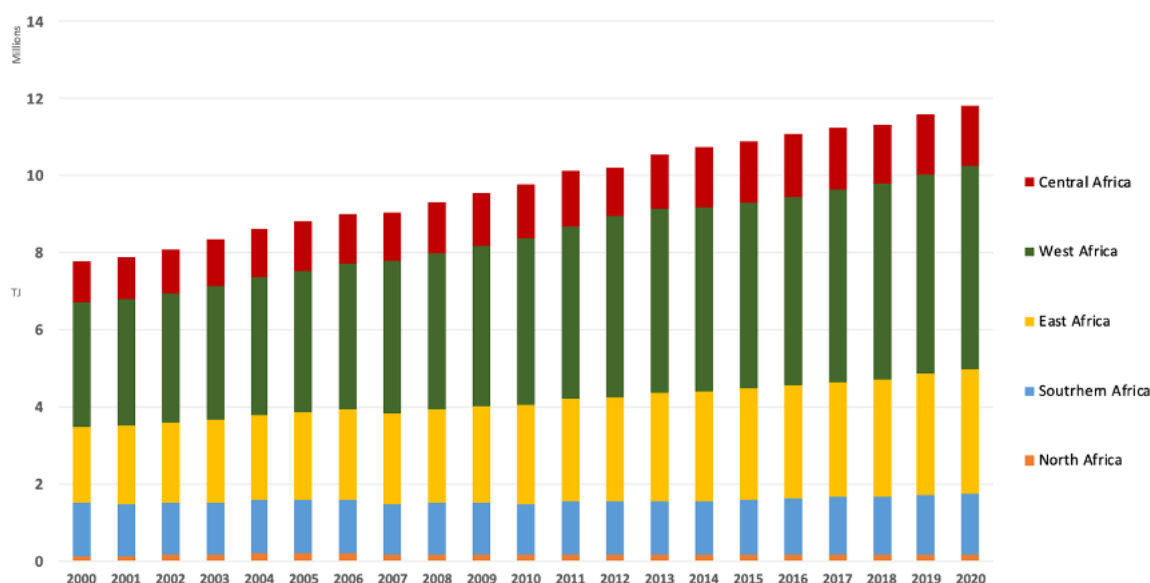
1.1.2 Current situation and trends

RE has shown significant growth in recent years in many parts of the world. While Africa's installed capacity is still far behind compared to other regions, representing only 1.7% of the global installed capacity, the continent has seen important growth. According to IRENA, the total installed capacity in Africa was 58784 MW in 2022 with hydropower and solar being the largest technologies with 38851 MW and 12641 MW, respectively.

As the installed capacity grew, renewables generation and consumption have also grown to reach 19192951 TJ and 15246458 TJ in 2020, as reported by the International Energy Agency (IEA) (IEA, 2023b). Solar and wind are the most consumed renewable sources in the continent with almost 80% of total renewable consumption. As shown in Figure 1.2, the largest consumers are West African and East African regions with an average consumption of 4280048 TJ and 2580250 TJ between 2000 and 2020, respectively. Based on IEA statistics, these two regions include the six largest African countries in terms of RE namely Nigeria, Ethiopia, Congo Republic, Tanzania, Kenya and Uganda. Nigeria registered the highest consumption in the last years accounting for 37645170 TJ on average. In 2019,

the share of RE in the total final consumption in the country represented 81.4%. This can be explained by the fact that Nigeria is the largest economy with an increasing GDP and the most populated in Africa thus its energy demand is among the highest in the continent (Ogbonnaya et al., 2019). In addition, the country has shown a serious commitment to renewable investments and according to IRENA, Nigeria is one of the top recipients in the world of public investments in renewables with 7639\$ million between 2011 and 2020.

Figure 1.2: Renewable energy consumption by African region (TJ) 2000-2020



Source: Own elaboration based on IEA statistics, 2023.

Ethiopia also is a heavy consumer of renewables with an average of 1232578 TJ between 2000 and 2020, despite having one of lowest energy consumption per capita in the continent. The country has an important share of RE consumption accounting for 88.9% of total final energy consumption. The high potential of natural sources in the country and the reduction in renewables costs have pushed their growth in Ethiopia, in addition to the growth of its energy demand as it is the second most populous country in Africa and the fastest growing economy (Oyewo et al. (2021)).

However, despite not having a large consumption of renewables, countries like Congo, Somalia and Gabon are considered the greenest countries and had the highest shares of RE in their total final energy consumption in 2019 with 96.24%, 95.03% and 89.88%, respectively (IEA, 2023a).

Based on IEA statistics, although Egypt and Morocco have devoted a huge commitment to renewables, North Africa remains the lowest in terms of RE consumption compared to the other regions, with an average of 170809 TJ from 2000 to 2020. Morocco and Egypt are the highest investors in RE after Nigeria accounting for 5322.84\$ million and 4775.66\$

million between 2009 and 2020, respectively ([IRENA \(2023\)](#)). As for Algeria, it is the lowest consumer of RE in the whole continent and registered 1544 TJ between 2000-2020 and its share of RE consumption was only 0.16% of the total in 2019. This is expected given that Algeria heavily relies on fossil fuels in its energy mix, it is a great producer and exporter of gas and oil and the country is ranked third and seventh in terms of gas and oil reserves in the world. At the same time, Algeria has great potential for renewable sources and since 2011, the country has tried to diversify its national energy mix by introducing new policies to enhance the development of renewables ([Zahraoui et al. \(2021\)](#)).

Southern countries such as South Africa, Mozambique and Zimbabwe have worked intensively in RE development. Mozambique and Zimbabwe had notable shares of RE in their final consumption of 79.5% and 81.5% in 2019, respectively. While for South Africa, even though the RE share is low compared with the region, the country covers the highest installed capacity of renewable technologies in all of Africa (recording 10445 MW in 2022 according to IRENA) as it is the most technologically advanced country in the continent ([Salahuddin et al. \(2019\)](#)).

All in all, most of the continent has manifested a huge interest in renewable sources and the national energy composition in different countries has been diversified, making modern sources an important part of it over the last years, and this growth of RE is due to different factors that influenced its spread.

1.2 Literature review on renewable energy determinants

The literature on RE development and related issues is wide but studies that focus on RE determinants and the factors that influence its deployment are considerably scarce due to the fact that it is a new area of research. Most of these studies were mainly concentrated on developed countries given that access to the data was much easier and those interested in developing countries are few, particularly those focusing on African countries. The available analyses on the RE determinants have highlighted different categories of drivers namely socio-economic, political, environmental, technological and country-specific factors.

[Marques et al. \(2010\)](#) have analysed the motivations that stimulate RE in 24 European countries over the period 1990-2006 applying fixed effects vector decomposition. They included in their analysis variables such as income, energy consumption, fossil fuels prices, energy imports, CO₂ emissions and other variables. Briefly, they concluded that the lobby of fossil fuels and CO₂ emissions does not encourage RE use in European countries, while the aim of gaining energy security is important to push RE development. Same for income but GDP is a RE driver, particularly in the European Union countries.

Including in their study investment variables in wind, solar photovoltaic, geothermal and

electricity from biomass and waste for 26 OECD countries over the period 1991-2004, [Popp et al. \(2011\)](#) discussed whether the technological change has an impact on RE investment. Using the PATSTAT database, they could obtain a comprehensive list of patents for the investment variables. In their findings, they pointed out that even if the impact of technological advancement is small, it contributes to greater investment, while investments in other energy sources such as hydropower and nuclear energy lead to less investments in renewables.

[Omri and Nguyen \(2014\)](#) carried out an analysis to examine the effects of economic development, oil prices, CO2 emissions and trade openness on RE consumption using a global panel for 64 countries between 1990 and 2011 and applying a dynamic system-GMM panel model. As a next step, they considered 3 subpanels based on the income levels of the countries: high-income, middle-income and low-income. Their results suggest that the changes in carbon emissions positively impact RE energy consumption in all subpanels studied and it is the same for the trade openness excluding the high-income sample. As for GDP per capita, they noticed a significant effect only for high- and low-income panels. And finally, oil price changes have a negative but small impact on the middle-income subpanel and the global sample that includes the 64 countries. These results contradict those found by [Kilinc-Ata \(2016\)](#) in his study on 27 EU countries and 50 US states from 1990 to 2011. The study mainly analyses the effectiveness of four instruments of RE policy namely feed in tariffs (FITS), tenders, tax and the most commonly used policy, quota in diffusing RE sources. Their findings showed that the first 3 categories FITS, tenders and tax incentives provided positive results on RE capacity in the countries and states studied while quota had no significant impact. Additionally, coal price, nuclear and electricity consumption are important factors to encourage RE deployment but income, security variables, gas price and CO2 emission are not.

In order to explore the relationship between RE consumption, Foreign Direct Investment (FDI) and GDP per capita in 31 Chinese provinces for the span time 2000-2015, [Fan and Hao \(2020\)](#) employed the unit root test, cointegration test and vector error-correction model. They confirmed that a long-term relationship and stationary equilibrium do exist between GDP per capita, FDI and RE consumption per capita. In the short run, RE consumption changes in China cannot be generated by FDI while in the long run, they will be boosted by a modest slowdown in GDP and FDI.

On the other hand, [Sweidan \(2021\)](#) examined in his study whether the geopolitical risk influences RE deployment in 10 net crude oil importer countries (Brazil, China, India, Indonesia, Malaysia, Philippines, South Africa, South Korea, Thailand and Turkey) from 1985 to 2017. The results of the Autoregressive Distributed Lag model (ARDL) suggest that geopolitical risk has a significant and positive impact on RE deployment and thus it is

not an obstacle but an incentive to RE diffusion.

Although there are plenty of studies on developed countries and large economies, research on the determinants of RE in Africa is relatively scarce. [Ackah and Kizys \(2015\)](#) for instance, conducted an analysis on RE demand determinants including GDP per capita, energy prices, energy consumption and carbon emissions in 12 oil-producing African countries for 42 years over the period 1971-2012. To do so, they made use of a one-way fixed effects model, a one-way random effects model and a dynamic panel data model. According to the results obtained, GDP per capita and energy consumption have an important positive effect on RE consumption while CO₂ emissions and energy price have an inverse impact.

Economic growth is the major determinant tested in the literature on RE consumption determinants. [Alabi et al. \(2017\)](#) studied this relationship in the long and short term for 3 African OPEC countries which are Algeria, Angola and Nigeria for the sample period 1971-2011, applying the Fully Modified Ordinary Least Squares model (FMOLS) for heterogeneous cointegrated panels. The findings confirmed the existence of a bi-directional causality relationship between GDP per capita and RE consumption in the short and long run. Further, they also found a bi-directional relationship between GDP and non-renewable energy, a bidirectional nexus between GDP and carbon emissions and a unidirectional causality running from non-renewable energy consumption to CO₂ emissions. In contrast, employing the Granger causality test and VECM method, [Ben Mbarek et al. \(2018\)](#) found that a unidirectional causal relationship exists running from GDP per capita to RE consumption in Tunisia between 1990 and 2015. In addition, they highlighted the bidirectional causalities existing between GDP per capita and greenhouse emissions and between greenhouse emissions and energy use. Also, a unidirectional nexus was discovered from CO₂ emissions to RE consumption and from energy use to GDP in the short term.

Adding other variables to those used in the study of [Ben Mbarek et al. \(2018\)](#), [da Silva et al. \(2018\)](#) investigated RE drivers in 17 Sub-Saharan African countries for 25 years (1990-2014) through the application of the panel-ARDL method. The authors pointed out that economic growth and the use of energy are positively correlated to RE and encourage its implementation in the Sub-Saharan region while fossil fuels price, CO₂ emission, imports, Kyoto Protocol ratification and population growth did not contribute to its integration in the period and countries included in the studies.

Contrary to [da Silva et al. \(2018\)](#), the link between economic development (GDP per capita) and RE was found to be negative in the analysis of [Ergun et al. \(2019\)](#) including 21 African countries over the period 1990-2013. The results of random-effects Generalized Least Squares regression used in their study revealed also that Human Development Indicator (HDI) negatively impacted RE deployment, FDI in the other hand showed a positive effect but the level of democracy did not manifest a direct relationship with RE.

Considering a sample of the most populated and largest economies in the 5 main regions in Africa which are Egypt, South Africa, Nigeria, Ethiopia and DR Congo, [Olanrewaju et al. \(2019\)](#) underlined how natural gas rents, oil and coal rents and carbon intensity interact with RE consumption. The fixed and random effects were applied to identify this interaction and suggested that only the gas rents have a positive nexus with RE consumption and as for oil and coal rents and carbon intensity, they were found to negatively influence RE consumption in the 5 countries between 1990 and 2015.

[Ankrah and Lin \(2020\)](#) discussed some of the previously mentioned factors in Ghana as a case study from 1980 and 2015, relying on a Vector Error Correction Model and Johansen cointegration technique. As a result, they obtained a positive relationship between FDI and RE and trade openness and RE, coinciding with the results of previous studies. GDP per capita, on the contrary, was found to be positive but insignificant and fossil development and financial development had a negative influence on renewable electricity.

Taking into consideration the factors mentioned above, the next section is going to discuss how the African countries differ in terms of RE, how these countries are devised and what factors can influence each group of countries.

1.3 Data and methodology

1.3.1 Data

To analyse RE development and its determinants in Africa, the research makes use of a set of variables bought and collected from different international databases as shown in Table 1 in the Appendix .1. The variables related to energy are the production and the consumption of both renewable and fossil energies, in addition to fossil fuel imports, and are included in the cluster analysis.

- **RE production:** is the total production of various technologies of RE namely hydropower, geothermal, solar photovoltaic, solar thermal, wind energy, tide energy, different types of bioenergy such as biogases, biogasoline and biodiesel and municipal waste.
- **RE consumption:** is the total consumption of the RE types as specified for the production.
- **Fossil fuels production:** is equal to the sum of the production of oil including oil shale and oil products, coal including coal and coal products and natural gas.
- **Fossil fuels consumption:** is equal to the sum of oil including oil shale and oil products, coal including coal and coal products and natural gas.

- **Fossil fuels imports:** are the sum of oil, coal and natural gas imports. For coal, it includes the external quantity obtained from other countries excluding coal in transit. As for oil imports, excluding the oil in transit, they comprise the amount of crude oil and oil products (under processing agreements). As reported by the World Energy Balances of the IEA, crude oil, NLG and natural gas imports are considered as received from the country of origin while refinery feedstocks and oil products are mentioned as coming from the country of last shipment. For the LNG which is imported from other countries, when it is exported to another country after the regasification process, it is considered import and export.

The other variables that are considered for discussing the factors influencing RE development in each cluster of countries are as follows:

- **GDP per capita:** the Gross Domestic Product divided by the midyear population.
- **Foreign Direct Investment:** the inflow of foreign direct investment into a country and it is equal to the sum of equity capital, reinvestment of earnings and other capital, according to the World Bank.
- **Trade openness:** the total of imports and exports of goods and services.
- **Political stability:** the political stability and absence of violence/ terrorism is an assessment of the political and security level within a country's political environment. It is an index that gives a score from roughly -2.5 to 2.5 for each country, in units of a standard normal distribution as described by the World Bank.
- **Level of democracy:** measures the access to political rights, civil liberties and the level of freedom in a country considering the right to vote and freedom of expression and equality before the law.
- **World Economic and Social Impact Index:** measures the economic and social situation within a country and it covers social indicators mainly related to education (years of schooling, education spend % of GDP, health (life expectancy, median age) and employment (population in employment). It gives a score ranging from 0 (poor) to 100 (very good).
- **CO2 emissions:** the emissions resulting from the consumption of fossil fuels mainly burning oil, gas and coal, from biomass and waste materials and from industrial processes such as the manufacture of cement.

The sample used in the work is chosen based on the availability of the data and includes 25 African countries ² over the period 2000-2020.

As shown in Table 2, the average RE consumption of all the countries in the sample ranges from a minimum of 674.37 registered in Equatorial Guinea to a maximum of 3764517.02 in Nigeria. The same as for the RE consumption, the lowest average production is recorded in Equatorial Guinea and the highest was for Nigeria. All in all, Nigeria is the highest African producer and consumer of RE with 5058970.4 TJ and 4639446.6 TJ in 2020, respectively while Equatorial Guinea is the lowest in terms of RE production and consumption accounting respectively for 3156 TJ and 145 TJ in 2020.

For fossil fuels, the maximum consumption was highlighted in South Africa with an average of 1680958.2 TJ and the minimum was registered in Eswatini accounting for 1834.92152 TJ. Fossil fuel production ranges between 687.77 TJ registered in Senegal and 5935617.6 TJ recorded in South Africa. The highest average imports of fossil energy were seen in South Africa and the lowest in Mozambique.

Based on the energy profiles of African countries and the data presented in Table 2, we expect to find different groups of countries as follows:

- The first cluster is expected to include high RE producers and consumers in the sample, such as Nigeria, Tanzania and DR Congo. These countries are characterised by high RE adoption and are supported by favourable policies, abundant natural resources and growing investments in RE infrastructure. For instance, Nigeria leads the continent in RE production and consumption, as previously described, driven by its large-scale hydropower and solar projects. Similarly, Tanzania and DR Congo benefit from substantial hydropower potential, making them key players in Africa's renewable energy landscape.
- The second cluster is likely to gather together countries with the highest average fossil fuel consumption and production. South Africa, with its heavy reliance on coal, is a main example of a fossil fuel-dependent economy. Algeria are also expected to belong to this cluster due to its significant oil and gas reserves and exports. Angola is also likely to be part of the same cluster due to its heavy dependence on oil and gas exports.
- The last cluster can be characterised by low energy production and consumption including Niger, Equatorial Guinea and Mozambique. These countries possess limited energy infrastructure and face significant challenges in accessing modern energy services.

²The countries included are Algeria, Angola, Botswana, Cameroon, Congo, Democratic Republic of Congo, Cote d'Ivoire, Egypt, Equatorial Guinea, Eswatini, Gabon, Ghana, Kenya, Libya, Morocco, Niger, Nigeria, Senegal, South Africa, Sudan, Tanzania, Tunisia, Zambia, Zimbabwe.

Table 3 summarises the variables that will be used to interpret the energy dynamics for the various countries. The average GDP per capita between 2000 and 2020 varies from a minimum of 356.08\$ recorded in the Democratic Republic of Congo to a maximum of 10403.65\$ in Equatorial Guinea. The most politically stable country is Botswana with an average index of 1.03 while the least stable is Sudan representing -2.14. The level of democracy in the continent is low with Ghana having the highest level of democracy score that is 80, and Egypt representing the least democratic country among the African countries studied in the analysis with a score of 5. The CO2 emissions in Africa are very low compared to developed countries with South Africa being the biggest emitter of CO2 with an average of 398484.34 kt and Eswatini being the least accounting for 1017.37 kt. As for FDI, the maximum average inflows are equivalent to 5239719047.62\$ and received by Egypt and the minimum inflows account for -426503104.16 in Angola. In terms of socio-economic situation, Algeria registers the highest World Economic and Social Impact Index equivalent to 73.9 and Mozambique represents the lowest score, 16.3. Finally, HDI ranges from an average of 0.72 in Libya and 0.34 in Niger.

Before conducting the cluster analysis, the correlation among the variables inserted in Table 3 was studied and the results of the correlation matrix are presented in Table 4.

The findings point out that:

- High FDI inflows are correlated with a high level of CO2 emissions.
- An advanced level of democracy results in a high level of political stability.
- High political stability increases trade openness and the GDP per capita.
- An elevated GDP per capita is accompanied by a better economic, and social situation and trade openness.

1.3.2 Methodology

In order to understand the behaviours of the African countries and to identify the possible similarities between them, the cluster analysis method was implemented. Cluster analysis is a set of multivariate techniques that aims to assemble objects and individuals into groups based on their similarities. It means that the elements belonging to the same cluster are similar to each other and have a high degree of association between them while those belonging to different clusters are dissimilar and have a low association, based on the variables included in the analysis ([Włodarczyk et al., 2021](#)). The clustering technique includes different methods such as k-means clustering, partitioning around medoids (PAM), Fuzzy C-means, K-medoids and hierarchical algorithms ([Janse van Vuuren and Vermeulen, 2019](#)). The present research is going to make use of Ward's method applied by [Kacperska et al.](#)

(2021) and W lodarczyk et al. (2021).

It is worth mentioning that the clustering algorithm is preceded by a similarity or dissimilarity measure and thus before conducting the cluster analysis it is necessary to consider a distance measure. The similarity measure consists of determining the relationship between the elements and the similarity between them (Maji et al., 2019). In this case, the Euclidean distance measure will be adopted as used by Kacperska et al. (2021) and W lodarczyk et al. (2021).

As a first step in the analysis, in order to have a similar scale, all 5 variables were standardised namely RE consumption, RE production, fossil fuels consumption, fossil fuels production and fossil fuels imports across all countries using the z-score method defined as follows:

$$Z_{ctv} = \frac{x_{ctv} - \bar{x}_{cv}}{\sigma_{x_{cv}}} \quad (1.1)$$

where v denotes the variable, c is the country, t refers to the year of the observation, Z_{ctv} is the value of variable v for country c at year t, $\bar{x}_{cv}$ refers to the mean of variable v for country c and $\sigma_{x_{cv}}$ is the standard deviation of variable v for country c as indicated in Table 2 in Appendix .1.

In the next step, the similarity between countries was determined by calculating the sum of the Euclidean distances d among the obtained z-scores and it is described as follows:

$$d_{ij}^2 = \sum_v \sum_t (Z_{itv} - Z_{jtv})^2 \quad (1.2)$$

where i and j refer to two countries within the dataset.

After calculating the distance between the countries included in the dataset, a cluster analysis was carried out, applying Ward's aggregation methodology. Through Ward's, the countries have been classified into clusters that are different to each other. In the last step, an analysis was conducted using the values included in Table 3 to characterise the different groups.

1.4 Results and discussion

1.4.1 Clustering results

After data normalisation and Euclidean distance measure among the scores resulting from the normalisation, the cluster analysis is run using Ward's method as previously described. The result provided a dendrogram as shown in Figure 1.3 including different possible clus-

ters. The optimal number of clusters was figured out based on optimizing data fitting by minimizing dissimilarities within clusters and maximizing dissimilarities between clusters to offer the most pertinent clusters. Four representative clusters are identified: cluster A, cluster B, cluster C and cluster D.

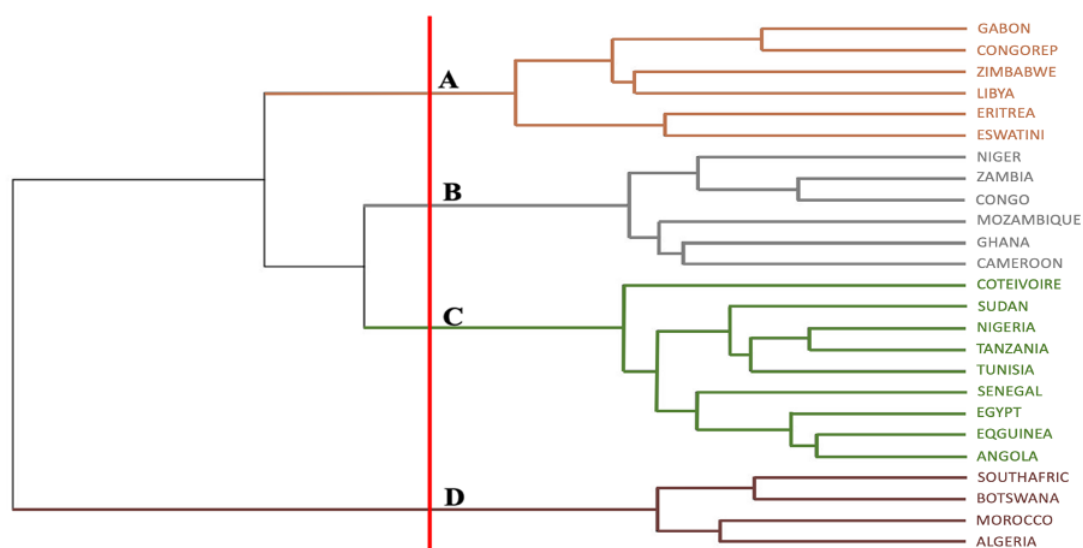
Observing the distribution of values in various groups, it is affirmed that the first cluster A groups a number of 6 countries namely Gabon, Dem Rep of Congo, Zimbabwe, Libya, Eritrea and Eswatini. It is characterised as the lowest importer and the most exporter of fossil fuels and they are labeled as “Brown dependent countries”.

Cluster B reunites 6 countries: Niger, Zambia, Congo, Mozambique, Ghana and Cameroon and it is found to be the least producer and consumer of energy. Countries of cluster B are identified as “Grey countries”.

Cluster C brings together 9 countries that are Côte d’Ivoire, Sudan, Nigeria, Tanzania, Tunisia, Senegal, Egypt, Equatorial Guinea and Angola. In this cluster, there are countries with the most use of RE which means the highest production and consumption of RE, and they can be considered “Green countries” (for instance Nigeria which is the largest producer and consumer of RE in the continent is part of it).

Lastly, cluster D includes 4 countries namely South Africa, Botswana, Morocco and Algeria and unlike cluster C, it is noticed to have the highest use of fossil fuels with the highest production and consumption of fossil fuels as the case of South Africa. So, they represent the “Brown countries” of Africa.

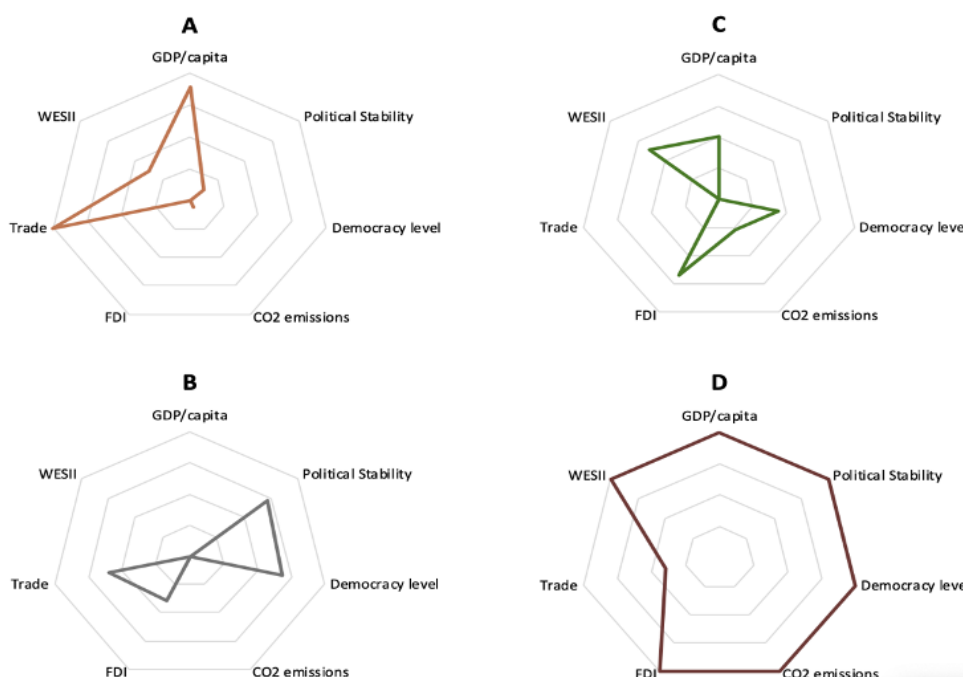
Figure 1.3: Cluster analysis results applying Ward’s method



Source: Authors elaboration.

As a last step, the work discusses the other socio-economic, political and environmental factors that explain each cluster using the variables included in Table 3. The results are presented in Table 5. Figure 1.4 presents the radar plot of the 4 clusters using the means of each variable included in Table 5 for each cluster. The values between -1 are constrained as a minimum and 1 as a maximum.

Figure 1.4: Radar plot for the 4 clusters



Source: Authors elaboration.

As shown, cluster A has the highest average of trade openness accounting for 80% of GDP and this could be explained by the fact that it takes advantage of energy commercial flows. Yet, the countries of this cluster are those who suffer the most from fragile political stability and low level of democracy and Libya is a good example of this.

On the other hand, cluster B characterised by low production and consumption of fossil fuels includes the least economically developed countries in the sample which have the lowest average GDP per capita compared to the other clusters and also have the lowest social conditions with an average World Economic and Social Impact index of 34.97.

Cluster C encompasses countries with high political instability but at the same time, they receive massive foreign investments, which demonstrates that an economy that is mainly based on RE may represent a great opportunity for investments and can be a lever for green economic development.

The last cluster D shows that major fossil fuel production in these countries is likely to lead

to internal economic and social development as they represent the highest average GDP per capita and the highest average World Economic and Social Impact index. However, cluster D has the highest CO₂ emissions confirming that high levels of fossil fuels production give rise to high degrees of CO₂ emissions.

1.4.2 Cluster framework and Policy Implications for SDGs Alignment

The United Nations Sustainable Development Goals (SDGs) stand as a global mandate to eradicate poverty, safeguard the environment, and ensure universal prosperity by 2030. These goals offer a comprehensive blueprint for tackling urgent global issues while nurturing sustainable progress across economic, social, and environmental spheres. Serving as a guiding framework, the SDGs rally governments, organizations, and communities worldwide toward a future marked by fairness, inclusivity, and sustainability. By addressing interconnected challenges like poverty, inequality, climate change, and environmental degradation, the SDGs endorse holistic development approaches that acknowledge the intricate relationships between diverse sectors and stakeholders ([United Nations, 2015](#)).

Within Cluster A, characterized by extensive trade openness and reliance on energy commerce, the focus lies on harnessing renewable energy sources to propel economic growth while concurrently tackling political instability and fortifying democratic institutions. This endeavour resonates with SDG 7 (Affordable and Clean Energy) by championing sustainable energy practices and SDG 16 (Peace, Justice, and Strong Institutions) by fostering stability and effective governance. Implementing policies to foster renewable energy adoption and sustainable infrastructure investment is vital, alongside efforts to fortify democratic structures and prioritize investments in education, healthcare, and social welfare to promote inclusive development and alleviate poverty.

Cluster B, marked by low fossil fuel production and consumption yet grappling with economic underdevelopment and social hurdles, necessitates targeted interventions to foster inclusive growth and diminish disparities. This corresponds with SDG 10 (Reduced Inequalities), underlining the significance of addressing income disparities and providing equal opportunities. Formulating strategies to promote economic diversification, create employment avenues beyond fossil fuel sectors, and invest in education and vocational training to empower marginalized communities are paramount. Equally critical is enhancing access to essential services like healthcare and sanitation to elevate living standards and well-being.

In Cluster C, characterized by political volatility alongside notable foreign investments, strategies must leverage renewable energy as a catalyst for sustainable economic advancement while concurrently addressing governance shortcomings. This is in line with SDG 9

(Industry, Innovation, and Infrastructure) by fostering innovation and infrastructure development and SDG 16 by promoting stable and inclusive governance. Establishing partnerships among governments, private sector entities, and civil society to attract sustainable investments in renewable energy, strengthening regulatory frameworks, and supporting peace building initiatives are imperative to mitigate political instability and foster sustainable development.

Lastly, Cluster D, emphasizing fossil fuel production and high CO₂ emissions, necessitates a shift toward cleaner energy sources to combat environmental degradation while safeguarding economic prosperity. This corresponds with SDG 7 and SDG 13 (Climate Action), advocating for clean energy solutions and climate change mitigation. Implementing policies to promote energy efficiency, introducing carbon pricing mechanisms, and investing in research and innovation to expedite the deployment of renewable energy solutions are vital within Cluster D to ensure a sustainable transition toward clean and renewable energy sources.

1.5 Conclusions of chapter 1

The present research discussed renewable energy development in the African continent during the last twenty years. First, it presented the current situation of renewable energy and how it is dispersed between countries, in addition to the factors that influence its deployment. Then, to understand the behaviours of the African countries and identify patterns, similarities and differences between them, a cluster analysis was performed using Ward's method on a sample of 25 African countries over the period 2000-2020. To do so, energy variables including renewable energy consumption, renewable energy production, fossil fuels consumption, fossil fuels production and fossil fuel imports were employed. The results of the cluster analysis suggest four groups of countries based on their energy dynamics. Cluster A has countries with the lowest imports and highest exports of fossil fuels. In cluster B there are the least producers and consumers of fossil fuels. Cluster C includes the most producers and consumers of renewable energy and countries in Cluster D are the most producers and consumers of fossil fuels.

The composition of each cluster is also explained by other variables employed in the analysis mainly socio-economic, political and environmental. The findings of the last analysis assume that, for the countries that belong to cluster A, the production of fossil fuels energy is boosted by foreign markets, so the transition can be arduous and linked to the relationships with the other countries. However, renewable energy could represent an opportunity for attracting foreign investments as long as policies that aim at improving the levels of

democracy in the various countries are implemented. The investments in renewables could be a driver for the economic and social development of countries comprised also in cluster B. In this cluster, the transition process could be easier because, due to the low production and consumption of fossils, the production of renewable energy can grow faster. In cluster C, the investments in renewable sources are correlated with an advanced level of Foreign Direct Investment. For these countries, it is expected green economic growth that could lead to better social conditions in the future, growing levels of democracy and greater political stability. The countries of cluster D should initiate renewable energy incentive policies as soon as possible in order to gradually substitute fossil fuels production and thus reduce the high CO₂ emissions. In this cluster, since the countries have developed economies and as a consequence, an important production and consumption of fossil fuels, the process of energy transition towards renewables may take more time and effort because it requires structural changes. For these countries, it can be supposed that there will be necessary changes in the supply and demand of energy resources, technological innovations and a new industrial policy.

Finally, the study suggests that further deep analysis of energy dynamics in these countries is needed in addition to country profile analysis for a better definition of policies to achieve a higher green economic development in the African continent.

Chapter 2

Renewable energy implementation as a pathway for energy security

The present chapter aims to investigate the contribution of renewable energy implementation to energy security. Also, it studies whether a greater use of renewables can minimise energy security risks in both developed and developing countries, with a particular focus on African countries. The work discusses the energy landscape of various countries by analysing their energy dynamics, specifically, it focuses on energy stocks that can give a better understanding of global energy security.

The analysis of this chapter is divided into two main parts. The first one shows the results of only African countries and in the second part, these results are compared with different samples. Thus, the first sample ¹ is conducted considering only African countries. The second sample ² examines these dynamics in European countries, and the third work ³ investigates a global sample of countries including developed and developing countries. Finally, the last work ⁴ extends the African sample and includes other developing countries from Asia and Latin America (Lesser-developed economies sample).

¹Stefano Fricano, Emna Kanzari, Gioacchino Fazio (2024). "Renewable Energy Integration and Stock Management: A Pathway to Energy Security in Africa". Under review by the *International Journal of Global Energy Issues*.

²Emna Kanzari, Stefano Fricano, Gioacchino Fazio (2024). "Analysing the energy stocks dynamics in European countries under an energy transition framework". In *Conflict Scenarios and Transitions. Opportunities and Risks for Regions and Territories*, volume 64 of *Scienze Regionali*, pages 305–326. Franco Angeli, 2024.

Presented and awarded at the XIX Annual Conference of the Spanish Association for Energy Economics.

³Emna Kanzari, Stefano Fricano, Gioacchino Fazio (2024). "Energy Stock Dynamics: Integrating Renewable Resources for Global Energy Security and Sustainability". Presented at XXI Workshop CiMET. Presented also at XXIII Annual Workshop SIEPI.

⁴Emna Kanzari, Stefano Fricano, Gioacchino Fazio, Roberto Cardinale (2024). "Energy reserve dynamics: Integrating renewable energy for energy security and sustainability in lesser-developed economies". Under review by *Energy Economics* for the call for papers: "Innovating towards a sustainable future: Decarbonisation strategies and energy economics in lesser-developed economies".

The rest of this chapter is organised into other four sections. The next one includes the previous analysis of the relationship between renewable energy use and energy security. The third section will present the data used to discuss this relationship and the methodological framework. In the last two sections, the main results obtained from the empirical analysis are presented for African countries and then for the rest of the samples. Lastly, the last section briefly concludes.

2.1 Literature review

According to different previous research, energy security can be realised through the realisation of its four main dimensions. [Gökgöz and Güvercin \(2018\)](#) reported that a secure energy source should be available in abundance, easily reachable regardless of any geographical or technological constraints, accessible at affordable costs and acceptable with low ecological footprints. Based on these criteria, renewable energy is available, accessible, affordable and acceptable, and therefore, it can promote energy security ([Kanzari et al. \(2024\)](#)).

Another important aspect of energy security is energy-sufficient supply. A single energy system, that depends only on fossil fuels, is not able to satisfy a stable supply of energy since they are finite and known for their scarcity ([Akrofi \(2021\)](#); [Holechek et al. \(2022\)](#)). Diversifying the energy system by including various alternatives such as solar, hydro, geothermal, wind and bio energies will add new capacities and provide a greater supply of energy and consequently greater energy security ([Aslani et al. \(2012\)](#)). Having a diversified energy mix will allow fossil importing countries, to gain self-sufficiency and reduce their reliance on external resources ([Khan et al. \(2023\)](#)). However, while for energy importing countries, enhancing energy supply is the main scope, for energy exporting countries, protecting energy demand security is a priority ([Bigerna et al. \(2023\)](#)). Fossil exporting countries mainly OPEC countries strongly depend on their export revenues, which contribute to their Gross Domestic Product (GDP). For instance, Saudi Arabia's oil sector represents alone approximately 40% of its GDP and around 70% of its total exports ([Gökçe et al. \(2024\)](#)). Consequently, depending on the energy dynamics in an economy, demand and supply security are of the same relevance ([Novikau \(2022\)](#); [Fan et al. \(2023\)](#)).

An important aspect to be considered is the fact that while diversifying the energy mix by including alternative resources as solar, wind, and hydro can enhance energy security by reducing dependence on finite fossil fuels, the inherent intermittency of some renewable energy sources can present a significant challenge. Solar and wind energies, for instance, are subject to variability due to weather and seasonal conditions, which can influence power availability and lead to fluctuations in energy supply ([van der Wiel et al., 2019](#)). These risks that may arise can be addressed by a combination of technology and policy solutions

to optimise the design and operational strategies for achieving high reliability. For example, using some energy storage systems, such as batteries and pumped hydro storage, can stabilise supply by storing excess energy during high generation periods for use during low performance periods ([Bhayo et al., 2020](#)).

The issue of energy security is the interest of every country worldwide, and the concerns about achieving it have become the focus of different governments and international organisations. The issue has been discussed by different scholars in the literature but less attention has been devoted to the interaction between energy security and renewable energy. A very recent study by [Kanzari et al. \(2024\)](#), has analysed the energy dynamics in 20 European countries between 1992 and 2020. Their findings show that renewable energy development leads to energy security in these countries through its effect on energy stock changes. According to the authors, countries with a secure energy system tend to maintain their reserves of energy low, while those with a fragile system maintain a high level of stocks. Also, they highlighted that when a country is an important player in the international market, either an importer or exporter, it keeps high stocks to react to any market fluctuation. Stock changes have not been considered before as a proxy for energy security, and since the concept is multifaceted, it is not easy to find an exact proxy. [Siksnelyte-Butkiene et al. \(2024\)](#) have analysed the existing indicators related to energy security and developed a new framework including 40 different energy security indicator sets and indices. The results underline that these sets and indices are unable to reflect all the fluctuations in the energy market, in addition to variations in economy, policy, international trade and other external macroeconomic factors. Using the Energy Security Risk Index, [Tugcu and Menegaki \(2024\)](#) investigated the relationship between renewable energy generation and energy security in G7 countries between 1980 and 2018. Employing the panel Autoregressive Distributed Lag (ARDL), panel quantile and quantile regression, and Dumitrescu-Hurlin panel Granger causality analyses, they revealed that the transition to renewable energy sources will enhance energy security. In specific, there is a unidirectional causality running from renewable energy to energy security in the short run, and it is found to minimize the risks related to energy security in the long run. Discussing the same relationship, [Belaïd et al. \(2023\)](#) showed that even though renewable energy could promote energy security, their investment levels are not enough to cover energy needs, in particular, with the current energy crisis that forced countries to reutilise fossil sources. Consequently, in the short and mid-term, fossil fuels will satisfy energy needs. Based on the conclusions of [Sattich et al. \(2022\)](#), the perceptions of energy security have been a key factor in designing energy policies in Lithuania. In light of the Europe-Russia crises, Lithuania's primary focus shifted to the use of renewables in order to gain energy independence since the country has one of the highest dependency rates in the European Union.

On the role of renewable energy consumption in alleviating energy poverty and enhancing energy efficiency, [Zhao et al. \(2022\)](#) assessed the energy poverty composite index on a global sample and explored the relationship between the variables. Their results indicate that global energy poverty can be mitigated and energy efficiency can be improved by accelerating clean energy development, and the effect is mostly seen in European countries. [Cergibozan \(2022\)](#) empirically tested how renewable energy sources may affect energy security risk for 23 OECD countries. Relying on second generation panel techniques, they concluded that between 1985 and 2016, renewable energy sources, in particular wind, hydroelectric and total renewables had a significant impact on reducing energy security risk in OECD countries. The findings show also that biomass and solar sources are found to be significant in explaining this relationship, and that there are remarkable differences in the results among the studied countries. Similar conclusions have been drawn by [Trifonov et al. \(2021\)](#) in their analysis of Eastern Europe, Caucasus and Central Asia (EECCA) countries. Although its impact is very low, renewable energy use has contributed to energy security in these countries, indicating a decrease in energy dependence. About Chinese energy security, [Wang et al. \(2018\)](#) applied a Divisia decomposition approach and scenario analysis to discuss how it can be affected by the use of renewable sources. Compared to fossil fuels, renewables not only can lead to energy security, but also to the reduction of CO₂ emissions in China, especially that the country is the world's largest CO₂ emitter. The same positive relationship was found also by [Brahim \(2014\)](#) for the Philippines, indicating how important are clean technologies to the country's energy security, since it has huge untapped renewable potential.

As the impact of renewable energy as a determinant of energy security is not enough discussed in the literature, this research dedicates attention to this regard, and intends to empirically investigate it for four different samples.

2.2 Model specification and Data

2.2.1 Data

To discuss the dynamics of the energy stocks, a set of energy indicators bought from the International Energy Agency (IEA) was adopted namely energy stock changes as a dependent variable and a set of explanatory variables including energy consumption and production, energy imports and exports and renewable energy production. Additionally, GDP growth has also been included to discuss the potential impact of the economic situation. The GDP growth is collected from the World Development Indicators.

The energy stock changes as defined by the International Energy Agency ([IEA \(2023b\)](#)), is the difference between stock levels on the first day and the last day of the year. These stocks

include the energy stocks held within a national territory by producers, importers, energy transformation industries and large consumers. A stock built is indicated by a negative value, and a stock draw by a positive number. Energy reserves or stocks can give valuable insights into the dynamics of the energy system. High levels of energy stocks indicate that a country has enough energy to overcome any risk related to energy. When a country has elevated reserves, it may handle supply interruptions. In the opposite case, when the stocks are low, it can signal potential challenges to manage supply shortages. Furthermore, in case of market shocks such as price volatility, countries with significant energy reserves can effectively control any possible risks.

In addition to energy stock changes, the analysis included the following variables as expressed in Table 2.1:

- **Renewable energy production:** is the sum of the production of renewable energy sources including wind energy, solar photovoltaic, solar thermal, hydropower, geothermal, tide energy, biogas, bio gasoline, biodiesel and municipal waste.
- **Energy production:** the total production of primary energy namely hard coal, lignite, peat, crude oil, natural gas liquids (NGLs), natural gas, biofuels and waste. It also involves nuclear, hydro, geothermal and solar as well as heat derived from heat pumps extracted from the ambient environment ([IEA \(2023b\)](#)).
- **Energy consumption:** total consumption in end-use sectors and non-energy use excluding energy used for transformation processes and for the internal operations of energy-producing industries. It represents the deliveries made for consumers ([IEA \(2023b\)](#)).
- **Energy imports:** the quantities that have crossed the country's national territorial borders whether customs clearance was completed or not. Coal is considered the quantities imported (excluding coal in transit) from other countries without considering the existence or the absence of an economic or customs union between them. For oil imports, it excludes oil in transit and includes crude oil and oil products imported under processing agreements. Crude oil, natural gas and natural gas liquids NGL are reported based on their country of origin, while refinery feedstocks and oil products are recorded based on the country of last consignment. Additionally, imported NGL that is later exported to another country after regasification is treated as both import and export ([IEA \(2023b\)](#)).
- **Energy exports:** the quantities that have crossed the country's national territorial borders whether customs clearance was completed or not. Coal is considered the

quantities exported (excluding coal in transit) to other countries without considering the existence or the absence of an economic or customs union between them. Oil exports include crude oil and oil products which are exported under processing agreements. For the imported oil for processing within bonded areas, when it is re-exported, it is recorded as exported from the processing country to the final destination. Additionally, imported NGL that is later exported to another country after regasification is treated as both import and export (IEA (2023b)).

- **GDP growth:** refers to the annual percentage increase of Gross Domestic Product at market prices using constant local currency. The aggregates are expressed in U.S. dollars (using constant 2015 prices).

Table 2.1: The variables considered in the work

Variables	Description	Source
Energy stock changes	Expressed in Terajoule (TJ)	IEA*
RE production	Expressed in TJ	IEA*
Energy production	Expressed in TJ	IEA*
Energy consumption	Expressed in TJ	IEA*
Energy imports	Expressed in TJ	IEA*
Energy exports	Expressed in TJ	IEA*
GDP growth	Annual percentage	WDI**

*Notes: *Data from the International Energy Agency, World Energy Balances (IEA (2023b)). **Data from the World Bank Group, DataBank, World Development Indicators (World Bank (2023)).*

The sample of countries ⁵ includes 13 countries from North and Sub-Saharan Africa. Unfortunately, For many African countries, there are no complete data and, in many cases, for data that goes back a long way, there are inconsistencies between the values from one year to the next. The countries were selected based on their availability (from 1992 to 2020) in order to have a panel that is as homogeneous as possible and with a representative number of countries. Table 2.2 shows the principal statistical characteristics of the sample (for details see Table 6 in the Appendix .1).

2.2.2 The variable selection and measurement

As already mentioned, the main interest of this work is to understand how greater renewable energy production may enhance energy security through energy stock dynamics.

The "stock change" variable, as referenced by the International Energy Agency (IEA),

⁵Algeria, Angola, Benin, Equatorial Guinea, Ethiopia, Gabon, Morocco, Mozambique, Nigeria, South Africa, Tunisia, Zambia and Zimbabwe.

Table 2.2: Descriptive statistics of the African sample (1992-2020)

Variable	Obs	Mean	Std. dev.	Min	Max
Stock changes					
RE production	327	0.494e+06	1.031e+06	962	5.058e+06
Energy production	327	2.316e+06	3.048e+06	4332	11.132e+06
Energy consumption	327	0.868e+06	1.237e+06	1664	5.733e+06
Energy imports	327	0.241e+06	0.350e+06	1107	1.505e+06
Energy exports	327	1.301e+06	1.786e+06	6	6.007e+06
GDP growth	327	4.606	11.105	-23.98	149.97

pertains to the variation or alteration in the levels of energy reserves or supplies over a specified period. Specifically, in the context of the IEA's analyses and reports, the stock change provides insights into the net increase or decrease in energy stockpiles, such as oil, gas, or coal, considering factors like production, imports, exports, and consumption. A negative number refers to a stock build while a positive number shows a stock draw (IEA (2023b)).

Following these indications, the interest was therefore to understand in which circumstances, for each country considered, there was an increase or decrease in energy stocks. When a country has sufficient energy produced domestically to satisfy its energy needs, it may be protected from global market fluctuations and geopolitical risks related to energy, and as a consequence, it keeps its reserves of energy low. In the opposite case, if a country is more exposed to the international market, it retains important reserves of energy to answer to the market's shocks. Lastly, an important condition for a country to increase its stocks is economic growth. To guarantee their growth process and maintain consistent production, countries have to keep important stocks of energy.

Therefore, the study's objective is to discuss the following suggested hypotheses:

H1: Greater energy production from renewable sources guarantees a more secure source of supply and can induce countries to reduce energy stocks.

H2: High capacity to meet internal energy demand through internal production can guarantee the stability of the internal market, and therefore makes high energy stocks less necessary.

H3: A country's greater exposure to international energy markets leads to maintaining high energy stocks.

H4: Economic growth trends can lead countries to accumulate energy stocks which can

be useful in guaranteeing the growth process.

To better answer these hypotheses, a set of explanatory energy variables (See Table 2.3) was built based on the variables presented in Table 2.1:

- **Energy production / Energy consumption:** the ratio between energy production and consumption used as an indicator to highlight the ability of a country to meet its energy needs by consuming what it produces. A high value indicates that the country produces more than it consumes and its domestic production satisfies its energy needs while a low ratio suggests that the country's energy sufficiency is low and may rely on foreign sources to fulfil its energy necessities.
- **Energy imports / Energy consumption:** The fraction between energy imports and energy consumption specifies the share of energy needs of a country that are met through importation compared to its energy consumption. It highlights the energy dependency on external energy imports: a low share means less dependency on the international energy market and higher energy security.
- **Energy exports / Energy production:** The ratio between energy exports and energy production represents the share of the total energy production of a country that is exported to other countries. A low value implies that the country uses its produced energy domestically and therefore has a limited economic interest in the international energy market as a supplier.
- **Renewable energy production / (Energy production + Energy imports – Energy exports):** refers to the share of renewable energy production in the total energy supply. It indicates the proportion of the energy generated from renewable resources compared to overall provided energy. This represents the variable of greatest interest since it could allow us to understand the relationship between renewable energy and the mitigation of energy risk.
- **GDP growth:** the variable GDP growth was included to take into account possible influences on economic growth which may be different for the various countries.
- **Country:** a fixed effect for each country was also considered by introducing an additional multinomial variable.

2.2.3 Model

To investigate the relationship between the variables described above, Probit analysis was implemented. Probit analysis is particularly appropriate when trying to estimate the effects

Table 2.3: Summary Variables

Variable	Description
Stock changes (Schng)	Dichotomous variable referred to Energy stock changes: “0” refers to a stock build while “1” to a stock draw.
% of RE in total energy supply (REshare)	RE production / (Energy production + Energy imports – Energy exports)
Energy Auto-Sufficiency (EAS)	Energy production / Energy consumption
Energy demand from foreign markets (EDF)	Energy imports / Energy consumption
Energy supply to foreign markets (ESF)	Energy exports / Energy production
GDP growth (GDPg)	Annual GDP growth
Country	Country fixed effects

of one or more independent variables on a binomial dependent variable (Wu et al. (2023)). Probit regression assumes that the relationship between the predictors and the probability of the response variable can be modelled using the cumulative distribution function (CDF) of a normal distribution. In other words, probit regression assumes that the probability of the response variable being equal to 1 can be modelled using a normal probability density function and that the values of the predictor variables determine the mean and standard deviation of the distribution (Hong et al. (2022)).

The study uses probit regression to model the relationship between the binary variable (**Schng**) and the predictor variables of Table 2.3. A dichotomous dependent variable was constructed which, starting from the sign of the stock changes variable (**Schng**), represents the possible underlying propensity towards a decrease in energy stocks ($Schng=1$) that fall along a continuum related to the level of energy security. The general specification of the model is as indicated in the following equation:

$$Pr(Stckchng_{it} = 1) = \theta(\beta_0 REshare_{it} + \beta_1 EAS + \beta_2 EDF_{it} + \beta_3 ESF_{it} + \beta_4 GDPg_{it} + u_{it}) \quad (2.1)$$

In equation 2.1, *Schng* presents the binary dependent variable, θ is the cumulative distribution function of standard normal distribution, *REshare*, *EAS*, *EDF*, *ESF* and *GDPg* are the explanatory and control variables, *i* stands for country, *j* refers to the year, β_0 , β_1 , β_2 , β_3 and β_4 are the parameters to be estimated, u_{it} represent the country fixed effects and ϵ_{it} is the error term.

2.3 Discussion

The findings of the probit analysis, as illustrated in Table 2.4, showed acceptance and rejections of the presented hypotheses. As expected, the coefficient for the share of renewable energy on the total energy supply (*REshare*) is significant and positive (5.47). This positive sign confirms that a greater use of renewable energy leads to lower energy reserves, indicating higher levels of energy security. Consequently, the first hypothesis **H1** regarding the positive contributions of renewable energy to energy security is accepted.

The lack of significance of the variable Energy auto-sufficiency (EAS) would seem to **deny Hypothesis H2** and, at first glance, it might appear uninteresting. However, this variable is very significant and reflects an important signal of the energy behaviour of the various countries. In fact, it tells us that the "current" ability to satisfy internal demand with internal production does not seem to sufficiently "ensure" the country's systems. This aspect is indeed intriguing and has also been emphasised by several analyses ([Dyatlov et al., 2020](#)), which underscore the fact that in certain countries where new initiatives for diversifying energy supply have been initiated, they stem from concerns regarding the lack of long-term guarantees offered by the current production capacity.

Also, the foreign market indicators, specifically Energy demand from foreign markets (EDF) and Energy supply to foreign markets (ESF) are both not significant and have negative coefficients. Although the parameters are not significant, the negative signs are noteworthy as they imply that increases in these variables lead to a lower probability of decreasing energy stocks. The fact that the parameters are not significant, while in other cases they have been, leads us to reflect especially from a perspective of different exposure to the international markets of African countries. When countries are involved in external markets as importers or exporters of energy, they tend to maintain high energy reserves to mitigate potential risks, such as supply disruptions or price fluctuations. By holding these substantial reserves, they can ensure a steady supply in the face of unexpected market changes.

A key characteristic of African countries in the international energy market is their reliance on energy imports. Many African nations lack the infrastructure and investment needed to exploit their own abundant natural resources, such as oil, natural gas, and renewable. Consequently, they import a substantial portion of their energy needs, making their economies vulnerable to external shocks and price fluctuations. This reliance on imports contrasts sharply with some of European countries, which have more diversified energy sources and greater investment in renewable energy technologies.

Moreover, African countries often have less influence in the global energy market compared to developed nations. This limited influence can make it challenging for African countries to secure favourable trade terms and manage the risks associated with energy imports and

exports. In contrast, developed countries, particularly in Europe, have established strong regulatory frameworks and strategic reserves that help stabilise their energy markets and mitigate risks.

Table 2.4: Probit results for the African sample

Cox&Snell PseudoR2:				
Pearson ChiSquare:				
Dependent variable:	Stock changes			
	Estimate	Std Err	z-Statistic	P-value
REshare	5.46914	1.50158	3.64226	0.000270
EAS	0.043187	0.0463156	0.93245	0.351104
EDF	-1.39335	1.19108	-1.16982	0.242073
ESF	-0.948422	0.656582	-1.44448	0.148603
GDPg	-0.006253	0.0137951	-0.453302	0.650331
Country effect				
Algeria	-1.05451	0.535722	-1.9684	0.049022
Angola	-5.17729	1.22138	-4.2389	0.000023
Benin	-4.13468	1.41781	-2.91625	0.003543
Equatorial Guinea	-1.52842	0.846261	-1.80608	0.070906
Ethiopia	-4.12084	1.50949	-2.72996	0.006334
Gabon	-4.71913	1.28647	-3.66827	0.000244
Morocco	-3.19717	1.57212	-2.03367	0.041985
Mozambique	-5.60964	1.50701	-3.72237	0.000197
Nigeria	-4.88589	1.28079	-3.81476	0.000136
South Africa	-1.48366	0.63083	-2.35191	0.018677
Tunisia	-2.55769	1.14891	-2.22618	0.026002
Zambia	-4.72503	1.45129	-3.25574	0.001131
Zimbabwe	-4.58193	1.1545	-3.96878	0.000072

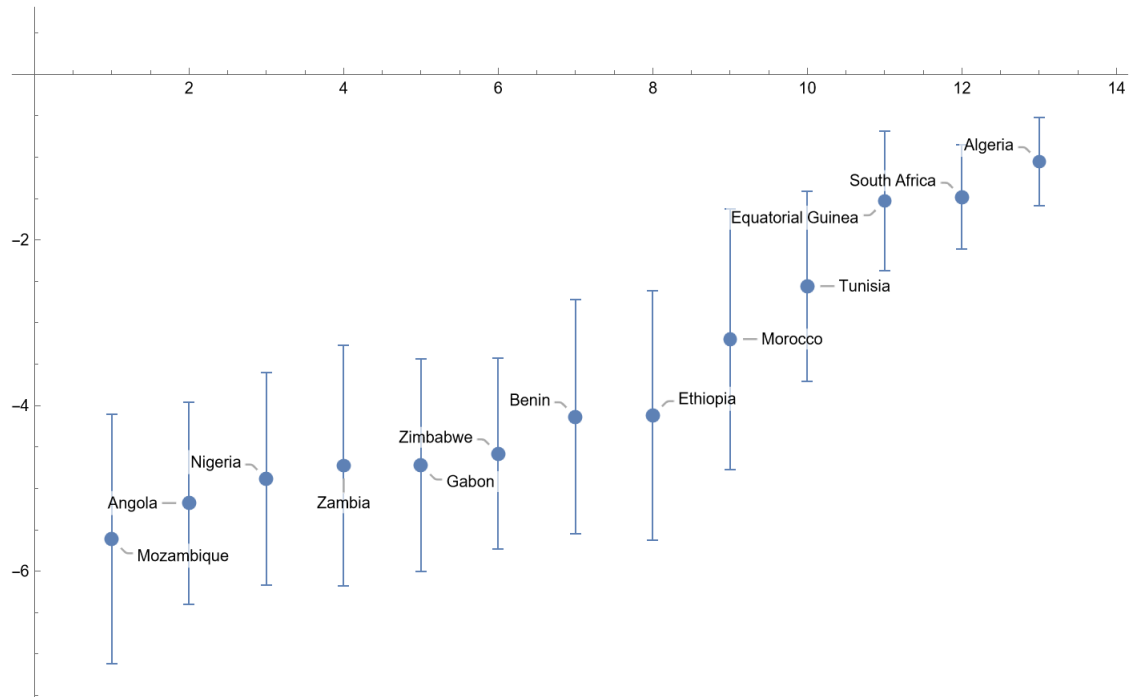
Notes: To carry out the Probit analyses, Mathematica's "ProbitModelFit function" was used [Mathematica \(2008\)](#).

Country fixed effects

The second part of the analysis included the country-fixed effects to account for differences between countries and focus on changes within each country over time. In fact, as demonstrated in Table 2.4 and Figure 2.1, the results show that for all countries the contribution of the fixed effect is significantly negative, indicating that the countries analysed had, overall in the analysed date range, a propensity to always increase energy stocks. The

estimated coefficients vary between -5.60964 and -1.05451 and as observed, there is no particular common trend is identified for these coefficients since the countries are not very different from each other.

Figure 2.1: African countries estimated parameters



Source: Authors elaboration.

2.4 Global view

After conducting the analysis on African countries, the work was extended to include other different countries since energy security can differ based on the needs and characteristics of each region. First, the analysis considered 20 European countries, then a global sample of 48 countries and lastly, a sample of developing economies including African countries used in the first sample in addition to the other developing countries. This section is organised according to the results of these samples, providing a comparative analysis between them.

2.4.1 Results of the European sample

The sample employed in this work includes variables for 20 European countries ⁶ between the available time span from 1992 to 2020. The largest 20 European countries in terms

⁶Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Netherlands, Norway, Poland, Poland, Romania, Spain, Sweden, Switzerland and UK.

of GDP have been chosen (see Table 7 and 8 in Appendix .1 for more details about the variables).

As can be noticed from the results in Table 2.5, similar to the first results, the variable measuring the amount of renewable energy produced in relation to all available energy (REshare) is significant. Both variables Energy auto-sufficiency (EAS) and GDP growth (GDPg) are not significant in this analysis, which is in line with the first findings on African countries. Whereas the variables related to the external market relationship namely the energy demand from foreign markets (EDF) and the energy supply to foreign markets (ESF) are found to be significant, which contradicts the previous outcomes.

For these variables, it is interesting to note that the sign of the coefficients is negative for both of them (-1.79274 and -0.757505): this confirms that greater exposure to international energy markets induces individual countries to keep high values of energy stocks instead of reducing them in order to contain the risk that may arise from price volatility. Indeed, when there is a price spike in the international market, energy importing countries (for example Germany, Italy, France, Netherlands, United Kingdom and Spain ([IEA, 2023a](#))) try to use their reserves of energy to stabilise domestic prices and for them it is important to have an abundant energy stock to better respond to the market. For these countries, it is important also to diversify their energy mix and include alternative resources as a hedge against price volatility and market pressures. In the opposite case, energy exporting countries tend to accumulate stocks to be able to respond promptly in case of a spike in external market demand (See paper 2 in Appendix .1 for more details).

The sign of the parameter linked to the portion of renewable energy out of the total available energy (Reshare) is again positive, confirming the previous coefficient for Africa. In fact, it shows how a greater percentage of available renewable energy is more likely to lead to a reduction in energy stocks. It is useful to remember in this case how this result is in line with European directives regarding the energy transition towards renewables (See paper 2 in Appendix .1 for more details).

Table 2.5: Probit results for the European sample

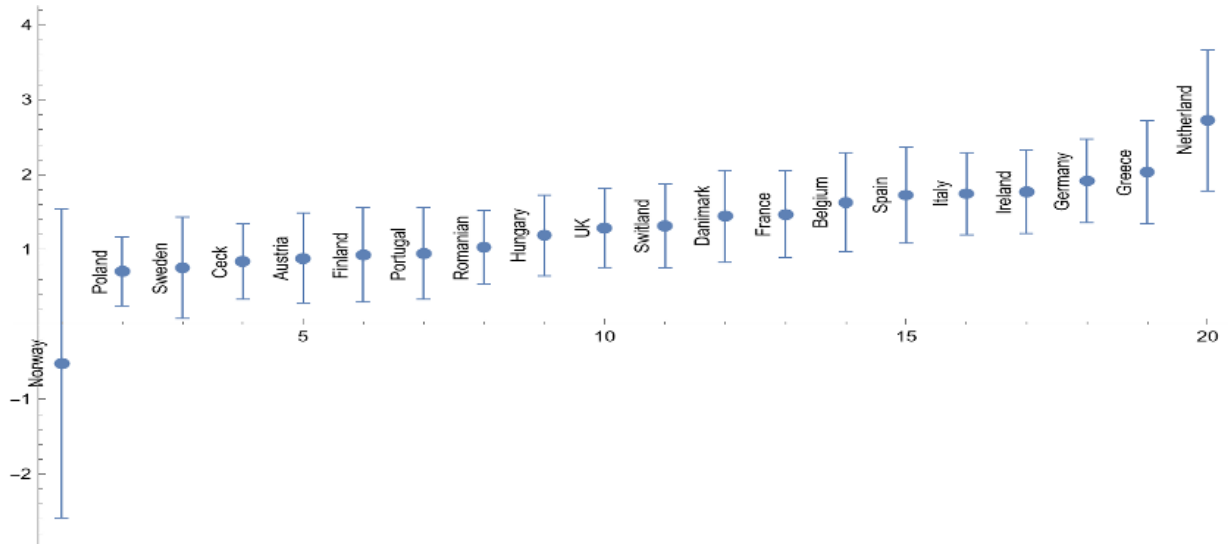
Cox&Snell PseudoR2:	0.3132			
Pearson ChiSquare:	638.5			
Dependent variable:	Stock changes			
	Estimate	Std Err	z-Statistic	P-value
REshare	3.079	1.566	1.966	0.049
EAS	-0.106	0.186	-0.572	0.567
EDF	-1.793	0.510	-3.517	0.001

ESF	-0.757	0.288	-2.634	0.008
GDPg	-0.020	0.018	-1.151	0.249
Country effect				
Austria	0.883	0.606	1.458	0.145
Belgium	1.631	0.662	2.465	0.014
Czech Republic	0.840	0.504	1.668	0.095
Denmark	1.447	0.616	2.349	0.019
Finland	0.927	0.626	1.480	0.139
France	1.470	0.578	2.540	0.011
Germany	1.917	0.563	3.403	0.001
Greece	2.036	0.687	2.964	0.003
Hungary	1.190	0.541	2.198	0.028
Ireland	1.772	0.552	3.207	0.001
Italy	1.748	0.553	3.157	0.001
Netherlands	2.730	0.941	2.901	0.004
Norway	-0.524	2.058	-0.255	0.799
Poland	0.710	0.456	1.558	0.119
Portugal	0.947	0.610	1.550	0.121
Romania	1.031	0.484	2.128	0.033
Spain	1.728	0.646	2.673	0.007
Sweden	0.759	0.678	1.118	0.263
Switzerland	1.315	0.566	2.322	0.020
UK	1.286	0.524	2.453	0.014

Country fixed effects

As for the first analysis, the country-fixed effects have been considered and they reserve careful discussion. Considering the country-fixed effects, it is noteworthy how the parameters related to the country-fixed effects are positive, except in the case of Norway for which the parameter, although the estimate has a very large standard error, takes on a negative value (see Figure 2.2).

Figure 2.2: European countries estimated parameters



Source: Authors elaboration.

This negative value is explained by the fact that, within the panel data, Norway is a unique case in which the value of energy production is much higher than domestic demand (approximately 5 times the average value of the other countries in the sample) and in this case, the level of energy risk appears to be considerably low, likely not linked to stock levels at all (See paper 2 in Appendix .1 for more details).

Excluding Norway, three distinct groups of countries can be identified, depending on the parameter values through the definition of some merely symbolic thresholds. The first group of countries is made up of six countries namely Poland, Sweden, Czech Republic, Austria, Finland and Portugal, for which the estimated best fit parameter takes on a value less than 1; for these countries, a general low propensity towards a decrease in stocks can be identified. For the countries of a second group which is composed of Romania, Hungary, Denmark, France, the UK and Switzerland, the estimated value of the parameter varies within a range of 1 and 1.5; for these countries, it is defined a general moderate propensity towards a decrease in stocks. Finally, for the countries belonging to the last group, the estimated parameters are greater than 1.5 with a maximum value of approximately 2.7 for the Netherlands. These countries have a greater propensity to decrease energy stocks probably because of a progressive transition towards the diversification of energy sources. This last result is interesting and deserves further analysis which could provide useful indications at a macroeconomic level on the nature of any exogenous or endogenous causes that may be at the basis of this variability.

2.4.2 Results of the global sample

The 48 countries ⁷ of the global sample were selected based on their GDP and also on their role on the international energy scene such as some OPEC countries. Based on the availability of the data, the sample ranges from 1992 to 2020 (for details see Tables 9 and 10 in the Appendix .1).

In line with expectations and as indicated in Table 2.6, the coefficient of renewable energy share in the total energy supply (Reshare) is significant and positive. The sign and significance level of the (Reshare) coefficient are the same in all samples, suggesting how strong is the relationship between these two variables, regardless of regional differences.

Contrary to the first sample (Africa) and similar to the second one (Europe), energy demand from foreign markets (EDF) and energy supply to foreign markets (ESF) are both significant and negative, confirming how energy security may be threatened by exposure to foreign markets.

As commonly understood, energy prices have shown remarkable variations in recent decades. As previously mentioned, when the prices in the energy markets surge, they represent a serious challenge to countries that massively import energy for their energy consumption. Countries such as the Netherlands, Belgium, Greece, Spain, Portugal, Italy, Ireland, Germany, Japan and Morocco, which have the highest dependency on energy imports (EDF), make use of their stored energy to maintain their use and stabilise domestic prices. Since the findings confirm that renewable energy is a key factor in providing a more reliable and secure energy system, these countries should focus on increasing renewable energy share in their energy mix to gain more independence and mitigate market pressures. However, as previously explained, in case of a price spike, exporting countries use their accumulated stocks to make higher revenues from their energy exports, in particular, the countries whose GDP is highly dependent on energy exports such as Russia.

Finally, energy auto-sufficiency (EAS) and GDP growth (GDPg) are not significant. The findings confirm those found for African and European countries on the relationship of these variables with stock changes.

⁷Algeria, Angola, Argentina, Australia, Austria, Belgium, Brazil, Canada, Chile, China, Colombia, Czech, Denmark, Ecuador, EqGuinea, Finland, France, Germany, Greece, Hungary, India, Indonesia, Iran, Ireland, Italy, Japan, Kenya, Korea, Mexico, Morocco, Netherlands, Nigeria, Norway, Peru, Poland, Portugal, Qatar, Romania, Russia, South Africa, Spain, Sweden, Switzerland, Thailand, Tunisia, Turkey, UK and USA.

Table 2.6: Probit results for the global sample

Cox&Snell PseudoR2:	0.3800145			
Pearson ChiSquare:	619			
Dependent variable:	Stock changes			
	Estimate	Std Err	z-Statistic	P-value
REshare	1.75866	0.875376	2.00903	0.0445338
EAS	0.024471	0.02171	1.12718	0.259667
EDF	-0.735369	0.322252	-2.28197	0.022491
ESF	-0.413171	0.207937	-1.98701	0.0469218
GDPg	0.00165311	0.00733866	0.22526	0.821777
	Country effect			
Algeria	-0.373029	0.304089	-1.22671	0.21993
Angola	-1.92255	0.602505	-3.19094	0.001418
Argentina	-0.273239	0.247669	-1.10324	0.269922
Australia	-0.448073	0.273193	-1.64013	0.100978
Austria	0.172786	0.412521	0.418854	0.675323
Belgium	0.248063	0.480345	0.516426	0.605557
Brazil	-0.703285	0.446439	-1.57532	0.115183
Canada	0.205766	0.296464	0.69407	0.487638
Ceck Republic	0.0389341	0.313794	0.124075	0.901256
Chile	-0.525395	0.453826	-1.1577	0.246986
China	-0.389673	0.276631	-1.40864	0.158942
Colombia	-0.72068	0.344335	-2.09296	0.0363525
Danimark	0.457302	0.369912	1.23625	0.216366
Ecuador	0.468737	0.304922	1.53723	0.124236
EqGuinea	-0.0348435	0.501651	-0.0694577	0.944625
Finland	0.229828	0.412827	0.556717	0.577721
France	0.449664	0.374512	1.20067	0.22988
Germany	0.891099	0.38065	2.341	0.0192323
Greece	0.625239	0.464994	1.34462	0.178748
Hungary	0.222307	0.367795	0.604432	0.545557
India	-0.818561	0.385671	-2.12243	0.0338014
Indonesia	-0.649342	0.378477	-1.71567	0.0862226
Iran	0.0114411	0.252227	0.0453601	0.96382
Ireland	0.595448	0.384413	1.54898	0.121386
Italy	0.73535	0.397255	1.85108	0.0641584
Japan	1.04469	0.467852	2.23295	0.0255522
Kenya	-1.64291	0.732414	-2.24314	0.0248877
Korea	0.0115509	0.464562	0.024864	0.980163

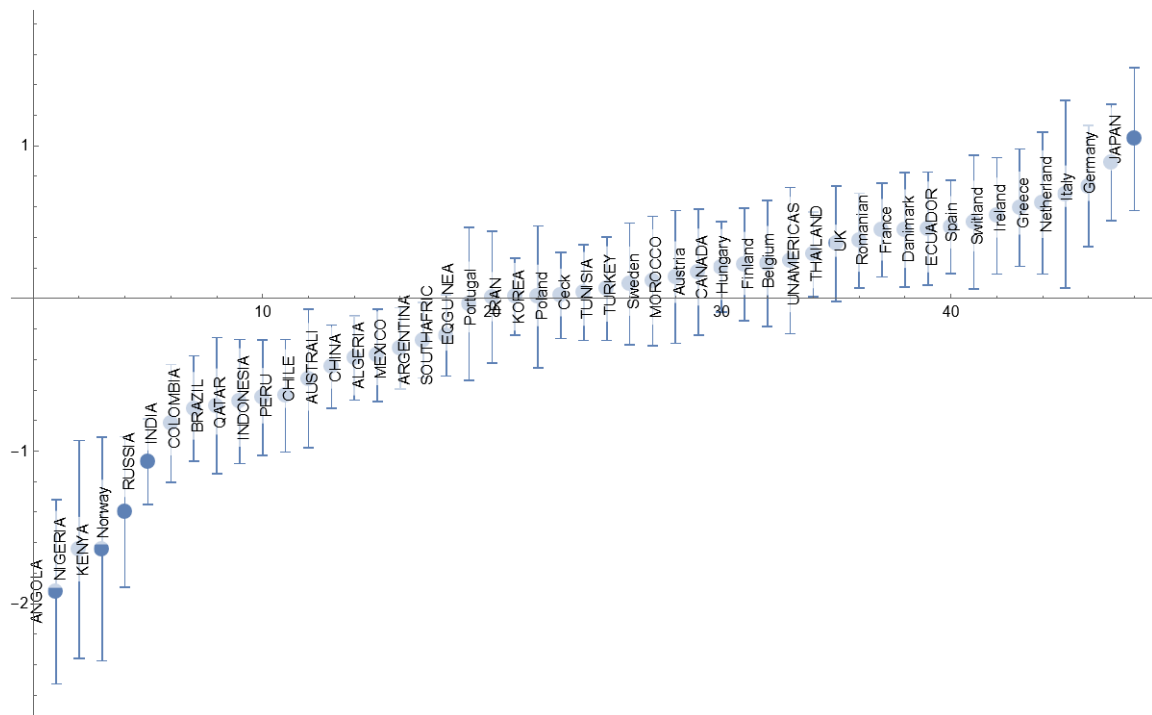
Mexico	-0.32654	0.26562	-1.22935	0.21894
Morocco	0.140428	0.434765	0.322997	0.746697
Netherlands	0.683513	0.614894	1.11159	0.266313
Nigeria	-1.64368	0.713385	-2.30406	0.0212194
Norway	-1.39947	0.493671	-2.83483	0.004585
Peru	-0.637439	0.369391	-1.72565	0.0844105
Poland	0.0197146	0.283328	0.0695822	0.944526
Portugal	0.00987114	0.431658	0.022868	0.981756
Qatar	-0.675696	0.40643	-1.66252	0.096409
Romania	0.44676	0.306965	1.45541	0.145556
Russia	-1.06909	0.280107	-3.81674	0.000135
South Africa	-0.242166	0.267328	-0.905876	0.365002
Spain	0.499249	0.437467	1.14123	0.253776
Sweden	0.113599	0.423335	0.268343	0.788435
Switzerland	0.540419	0.381333	1.41718	0.15643
Thailand	0.35902	0.377089	0.952082	0.341055
Tunisia	0.0627598	0.338169	0.185587	0.852768
Turkey	0.0944824	0.39947	0.236519	0.81303
UK	0.37816	0.310916	1.21628	0.223879
USA	0.28813	0.277003	1.04017	0.298262

Country fixed effects

The second part of Table 2.6 presents the country-fixed effects results, showing a divergence in the coefficients obtained. The coefficients vary from -1.92225 to 1.04469. As illustrated in Figure 2.3, three groups of countries were distinguished based on their coefficients. The first group includes countries with strong negative coefficients: Angola, Nigeria, Kenya, Norway, Russia, India, Colombia, Brazil, Qatar, Indonesia, Peru, Chile, Australia, China, Algeria, Mexico and Argentina, and it ranges from around -1.93 to -0.24. These countries have a strong tendency to increase their energy stocks. The second group varies from -0.035 to 0.25, and it is composed of South Africa, Equatorial Guinea, Portugal, Iran, Korea, Poland, Czech Republic, Tunisia, Turkey, Sweden, Morocco, Austria, Canada, Hungary, Finland and Belgium. This group has coefficients close to 0 and shows a balanced propensity towards decreasing their stocks. The last group has the highest coefficients ranging from approximately 0.3 and 1.05. The USA, Thailand, UK, Romania, France, Denmark, Ecuador, Spain, Switzerland, Ireland, Greece, Netherlands, Italy, Germany and Japan belong to this group. The high coefficients indicate a strong propensity to decrease energy stocks.

As observed from these groups, the dynamics of the energy system are highly complex, for example, some of the countries of the first group, such as Angola and Norway, have high production and exports of energy and have also high production of renewable production. In this situation, it is quite complicated to balance between keeping high stocks of energy to exporting them on the international market, or increasing renewable production and reducing these stocks.

Figure 2.3: Countries estimated parameters for the global sample



Source: Authors elaboration.

2.4.3 Results of the lesser-developed countries sample

The last part of the analysis takes into account the African countries employed in the first sample and another group of developing countries from Asia and Latin America. In total, 31 countries ⁸ from lesser-developed economies with the lowest GDP per capita were selected between the same time span 1992-2020. (See Tables 11 and 12 in Appendix .1).

Starting with the first variable (REshare), exactly as the rest of the previous three samples, it is significant and positive. This result confirms again the significant role played by

⁸Algeria, Angola, Benin, Bolivia, Brazil, Colombia, Ecuador, Equatorial Guinea, Ethiopia, Gabon, Guatemala, Honduras, India, Indonesia, Jamaica, Mongolia, Morocco, Mozambique, Myanmar, Nicaragua, Nigeria, Pakistan, Peru, Philippines, South Africa, Sri Lanka, Thailand, Tunisia, Vietnam, Zambia and Zimbabwe.

renewables in achieving energy security in different developing and developed countries. It is highly important to consider this result, especially for countries encountering serious energy security risks.

Our results also show that self-sufficiency, calculated in our independent variable EAS with a fraction between energy production and consumption, is not statistically significant. While this does not confirm one of our hypotheses, and specifically H2, this result can be explained by the fact that most countries in this sample have not significantly changed their levels of self-sufficiency during the years analysed. In other words, in the period 1992-2000, most countries in this sample remained either exporters or importers (or self-sufficient), without witnessing significant structural changes in this specific aspect.

The findings on the variables related to exposure to the international energy market are debatable. They showed contradiction to the earlier explanations. The indicator energy supply to foreign markets (ESF), which indicates a country's exposure to international markets as an energy exporter, is not significant in explaining the energy stock changes. The lack of significant change in energy reserves as a result of fluctuations in the markets for fossil fuels export can be explained by the fact that exporting countries usually organise their production and contractual arrangements to balance short-term international fluctuations of demand and prices.

By contrast, the indicator of energy demand from foreign markets (EDF), showing a country's exposure to international markets as an energy importer, is significant and positive. This result is entirely opposite to all those obtained from the previous samples, where increases in foreign energy supply and demand had different impacts. The positive sign shows how a structural decrease in the levels of imports induces a decrease also in the levels of energy reserves. This suggests that importing countries tend to decrease reserves when they succeed to decrease their levels of energy imports. This occurs for example when the countries experience a significant increase in the domestic production of renewable energy. This is especially important in lesser-developed economies, which are particularly vulnerable to the high costs of energy imports. They tend to decrease the levels of energy reserves also due to the high costs associated with capital and operating costs of storage infrastructure, which corresponds to around 10% of the final commodity price ([Oxera, 2010](#)).

Lastly, the indicator GDP is not significant, and hypothesis 4, namely that economic growth requires higher energy reserves, is not confirmed. The hypothesis was particularly relevant in the context of lesser-developed economies, which usually grow at higher rates as compared to advanced economies. This result can be interpreted by the fact that additional energy required to grow was often met by new supplies deriving from domestic production and import, including from additional domestic renewable energy production, the latter not requiring higher energy reserves.

Table 2.7: Probit results for lesser-developed countries

Cox&Snell PseudoR2:	0.2145			
Pearson ChiSquare:	733.12			
Dependent variable:	Stock changes			
	Estimate	Standard Error	z-Statistic	P-Value
REshare	3.04048	0.84902	3.58116	0.00034
EAS	0.015364	0.0320224	0.479789	0.631377
EDF	1.48867	0.60217	2.47218	0.013429
ESF	0.256307	0.294356	0.870739	0.383897
GDPg	0.006038	0.0112781	0.535338	0.592416
	Country effect			
Algeria	-0.392024	0.348752	-1.12408	0.260981
Angola	-3.00198	0.695023	-4.31924	0.000016
Benin	-2.54544	0.809	-3.1464	0.001653
Bolivia	-1.17143	0.351812	-3.3297	0.000870
Brazil	-1.94991	0.540066	-3.61051	0.000306
Colombia	-1.1742	0.39767	-2.95271	0.003150
Ecuador	-0.246573	0.429302	-0.574359	0.565725
Equatorial Guinea	-0.453663	0.599023	-0.757337	0.448848
Ethiopia	-1.94497	0.917347	-2.12021	0.033988
Gabon	-2.23397	0.749246	-2.98163	0.002867
Guatemala	-3.05481	0.756283	-4.03924	0.000054
Honduras	-2.24523	0.743867	-3.01832	0.002542
India	-2.24133	0.526481	-4.2572	0.000021
Indonesia	-1.42705	0.475546	-3.00087	0.002692
Jamaica	-2.50169	1.00434	-2.49088	0.012743
Mongolia	-1.04155	0.34387	-3.02889	0.002455
Morocco	-2.76544	0.840442	-3.29046	0.001000
Mozambique	-3.30017	0.867011	-3.80638	0.000141
Myanmar	-2.40858	0.699404	-3.44376	0.000574
Nicaragua	-2.8339	0.793069	-3.57334	0.000352
Nigeria	-2.62275	0.745774	-3.51681	0.000437
Pakistan	-1.33347	0.52925	-2.51955	0.011751
Peru	-2.05672	0.53041	-3.87761	0.000105
Philippine	-2.36176	0.817316	-2.88965	0.003857
South Africa	-1.06619	0.385498	-2.76575	0.005679
Sri Lanka	-1.67456	0.749684	-2.23369	0.025504
Thailand	-1.62424	0.618983	-2.62405	0.008689
Tunisia	-1.99428	0.63141	-3.15846	0.001586
Vietnam	-2.16263	0.55873	-3.87061	0.000109
Zambia	-2.6071	0.833784	-3.12682	0.001767
Zimbabwe	-2.97581	0.672778	-4.42316	0.000009

In-Depth Country Group Analysis

While the above findings provide evidence of general trends among lesser-developed economies on the relation between the production of renewable energy and stock changes, the sample includes countries that are quite diverse among each other in terms of population, energy production, import & export, GDP, industrial and technological capabilities, and geographical specificities.

For this reason, the sample was divided into groups with more homogenous features. The main differences concern the size of the economy and population, with middle and large countries identified as those with a population higher than 45 million; and whether they are major exporters with exports accounting for more than 50% of their energy production, or self-sufficient and importer of fossil fuels. Group A includes middle and large exporting countries, namely Algeria, Colombia, Indonesia and Nigeria. Group B comprises middle and large self-sufficient and importing countries such as Brazil, Ethiopia, India, Myanmar, Pakistan, Philippines, South Africa, Thailand, Vietnam. Group C includes small exporting countries such as Angola, Bolivia, Ecuador, Equatorial Guinea, Gabon, Jamaica, Tunisia. Lastly, Group D comprises small importing countries such as Benin, Guatemala, Honduras, Mongolia, Morocco, Mozambique, Nicaragua, Peru, Sri Lanka, Zambia and Zimbabwe. The analysis that follows on the different groups of countries is based on the results shown in Table 13, in which the value of the main variables of interest for this paper have calculated (as summarised in Table 13 in Appendix .1).

A surprising trend emerges for Group A of large exporting countries (See Table 2.8). Despite their economy is heavily reliant on fossil fuels, in the period from 1992 to 2020 many of them have reduced their reserves of fossil fuels in the years, and specifically in a range between 31% to 58% of the years considered in our analysis. This can be explained by an increase in the share of renewable energy, which, in their energy mix now accounts between 20% to 78%. The reduction of fossil fuel reserves can be explained by their strategy to increase their share of renewables to meet domestic energy consumption, while keeping fossil fuels as a commodity for export and as a source of commercial surpluses. This requires less energy reserves, and the disposal of old storage infrastructure for the balancing of domestic and export reserves. The only exception in this group of countries is Algeria, who was able to reach a share of renewables of only 0.2%, as foreign investments were lower than expected due to regulatory and macroeconomic factors that discouraged them ([Cardinale, 2023](#)). The decrease in Algerian energy reserves can be explained by its increasing reliance on long-term export contracts ([Darbouche \(2010\)](#); [Cardinale \(2019\)](#)) and the subsequent reduction of the export uncertainty on both volumes and prices.

Table 2.8: The identified groups

Group A	Group B	Group C	Group D
Algeria Colombia Indonesia Nigeria	Brazil Ethiopia India Myanmar Pakistan Philippines South Africa Thailand Vietnam	Angola Bolivia Ecuador EqGuinea Gabon Jamaica Tunisia	Benin Guatemala Honduras Mongolia Morocco Mozambique Nicaragua Peru Sri Lanka Zambia Zimbabwe
<i>Middle and large exporting countries</i>	<i>Middle and large self-sufficient and importing countries</i>	<i>Small exporting countries</i>	<i>Small importing countries</i>

A similar trend occurred for Group B of middle and large self-sufficient and importing countries. However, the share of renewables in the energy mix is higher in most of these countries, while stock changes are similar to those observed in Group A. This can be explained by the fact that importing countries, especially when of middle or large sizes, face a significant energy supply (or import) risk. Their diversification to renewables has led to a reduction of their energy reserves across several years, although not to a great extent due to the above-mentioned vulnerability on imported supplies.

There are exceptions for South Africa and India. South Africa has a share of renewable energy that is rather low, corresponding to 7% of the energy mix, while its energy reserves have decreased in more than 40% of the years analysed (1992-2020). This can be explained by South Africa's increasing consumption of domestically produced coal ([Prevost, 2013](#)), which has sorted the same effect of renewables in providing confidence over enhanced energy security. By contrast, the case of India shows a limited increase in renewables in the energy mix and a similarly limited change in energy reserves, namely a reduction in about 27% of the years considered. While the limited growth of renewables in the energy mix can be explained by the extremely big size of the Indian economy and population, the equally limited change in energy reserves confirms our hypothesis that India has been cautious to reduce them as their dependence on imported fossil fuels has increased over the years and today it remains significant. For example, while it used to import about 0.4 million barrels of oil per day in 1990, this number reached 4.4 million in 2018 ([Bhatt, 2020](#)), which

represents around 80% of its oil consumption.

Group C of small exporting countries shows an even more pronounced trend of reduction of energy reserves as renewable energy increases in the energy mix. This is especially evident in countries with very small population ranging from 1 to 5 million such as Equatorial Guinea, Gabon and Jamaica. This can be interpreted as a result of their flexibility and ease in meeting the energy needs of the population, and a perception of enhanced energy security as renewable energy capacity increases. By contrast, small countries in this group that are closer to the medium size, for example, those with populations in the range between 12 to 35 million show a variety of cases.

For example, Angola has not experienced a significant reduction in fossil fuel reserves in the years considered, despite renewables now account for more than 50% in the energy mix. One of the main reasons could be related to its geographic position far from the main consumption markets in Europe and Asia. As a result, its oil & gas exports do not take place through pipelines, which usually entails more stability in the volumes and prices exported, but through oil and Liquefied Natural Gas (LNG) tankers. This type of infrastructure involves a more diversified range of customers, and in the case of Angola also a significant share of spot and short-term export contracts ([Angola LNG, 2024](#)), which entails a higher commercial uncertainty thus the need to keep higher reserves.

By contrast, Bolivia has witnessed decreased energy reserves across a higher number of years, despite renewables account for only 20% of its energy mix. This can be also explained by Bolivia's geographic specificity of being a landlock country, which allows exports only only to two customers, namely Argentina and Brazil, and through the two pipelines Yabog and Gasbol. By also relying on long-term export contracts, this market setting provides low commercial uncertainty and thus more flexibility to lower reserves ([Mares, 2004](#)). In a similar way, Ecuador has seen a reduction in energy reserves for several years in correspondence to an increase in renewables, and thanks to consolidated oil export relations with the main buyers (US, China, Japan, India and Chile) supported by contractual arrangements providing guarantees on volumes and prices such as 'oil futures' ([EIA, 2023](#)). Tunisia is a distinct case as it is an exporter without being a producer because it is a transit country for Algerian gas to Italy. Its willingness to reduce reserves as its renewables increased up to covering 20% of the energy mix can be explained by the minimal uncertainty that long-term contracts will not be respected ([Hayes, 2006](#)), due to Algeria's strong interest in exporting and Italy's strong interest in importing, both through the Tunisian gas corridor.

Lastly, Group D of small importing countries also shows a heterogeneity of cases within the trend of decreasing reserves in the face of increasing renewables in the energy mix. Most of them shows average levels of decreased energy reserves in the face of exceptionally high

levels of renewables in the energy mix. This is the case of Benin, Guatemala, Honduras, Mozambique, Nicaragua and Zambia. Their reserves have decreased between 34% to 58% of the years analysed with a share of renewables that ranges from 50% to 90%. This prevailing trend can be explained by the energy security concern that small importing countries have, and their willingness to keep spare storage capacity despite the high levels of self-sufficiency reached thanks to the dominance of renewables in the energy mix.

By contrast, Mongolia, Morocco and Peru show similar or slightly less reserve changes annually but in the face of much lower levels of renewables in the energy mix. For Morocco and Peru, this trend can be explained because they are transit countries in which natural gas pipeline crosses their territory to reach large consumption markets such as Spain and Chile (Mares (2004); Ouki (2021)). For this reason, gas supplies are guaranteed by their strategic location and by long-term transit and supply contracts.

Mongolia's energy security guarantees derive instead from the local abundance of coal, which makes the country almost self-sufficient, together with other renewable sources (Liu, 2024). Sri Lanka is a unique case showing a very significant stock reduction of 82% in the face of 54% renewables, with this confidence probably deriving from a diversified energy mix (oil, coal, hydro, waste and biofuels), largely from domestic sources, and its strategic position as hub between Indian and East Asian refineries of abundant Russian and Middle East crude oil. Lastly, Zimbabwe shows limited stock changes in the face of over 60% of renewables in the energy mix, which can be explained by its isolated positioning as a landlock country in Southeast Africa, far from relevant markets for energy production and consumption.

2.5 Conclusions of chapter 2

Energy security has become a priority for different nations since it is important for their national security, growth process and energy independence. Recently, the concept has gained international attention and various governments have integrated the goal of achieving energy security into their national plans and policies. The global efforts have underlined the use of renewable energy as an important tool in ensuring each aspect of energy security, including environmental, economic and geopolitical aspects. As commonly understood, energy security touches different aspects, and it may be prioritised based on the energy characteristics of different economies.

For African countries and some other developing countries, ensuring a stable and affordable energy supply is essential for supporting economic growth, reducing poverty, and improving the living standards of millions of people across the continent. However, many developing countries face significant challenges in achieving energy security due to underdeveloped

infrastructure, political instability, and high dependency on energy imports.

For some European countries, a stable and secure energy system is important to reduce energy imports from foreign sources and gain energy dependence as most of them lack energy auto-sufficiency and heavily depend on foreign suppliers.

For some leading economies, energy security can be manifested differently. Although having a sufficient supply of energy, these countries face the challenge of reducing their CO₂ emissions and gain environment sustainability.

One of the primary consequences of inadequate energy security is the need to accumulate large energy stocks. Countries with insufficient domestic energy production are compelled to maintain substantial reserves of energy resources, such as oil, natural gas, and coal, to safeguard against supply disruptions. These energy stocks serve as a reserve to manage potential shortages caused by geopolitical tensions, market volatility, or natural disasters.

Using a panel sample for the period between 1992 and 2020, a Probit estimation model was applied considering the sign of energy stock changes as the binary dependent variable and the share of renewable energy in total energy supply as the main independent variable. Other energy related variables were also included mainly the energy auto-sufficiency and two variables related to the external market relationship which are the energy demand from foreign markets and the energy supply to foreign markets. The main conclusions are as follows.

- Countries having an important share of renewables in their energy supply are likely to decrease their energy stocks as they are not much exposed to market fluctuations.
- The exposure to foreign energy markets is highly linked to energy security risks, which means that those countries tend to increase their stocks to overcome the market risks.

Lastly, based on the Probit findings, different groups of countries were identified for each sample according to the coefficients obtained from employing country-fixed effects in the analysis. It was expected to discover common energy tendencies for each group or, alternatively, identify shared economic and social factors that could better explain the formation of these groups. However, this aspect remains ambiguous in the analysis and it warrants deeper attention in future research.

Chapter 3

Chinese Foreign Direct Investment Impacts (CFDI) on Energy Poverty

The third chapter discusses in more detail energy poverty, one of the relevant aspects of Africa's energy security risks. It aims to study what effects have FDI from China on energy poverty in African countries since Chinese firms have been strongly present in the continent, investing in sectors that may positively impact access to electricity.

The present work seeks to contribute to the existing literature on energy poverty determinants by studying in particular Chinese FDI's contribution to energy generation and access, which to the best of available knowledge, is the first work dedicated to analysing this aspect. It is worth noting that this analysis is based on a previous work ¹ on the relationship between CFDI and poverty reduction in Africa (see Appendix .1 for the detailed paper). To make connections between both topics, the chapter investigates the relationship between CFDI and a dimension of poverty which is energy poverty. The work was developed in collaboration with the Nanjing University of Science and Technology during my visiting period and part of it is published in the IAEE Energy Forum ² (see Appendix .1 for the published paper).

The next part of this chapter provides an overview of FDI in Africa. The following part presents the literature review of the investigated relationship. After that, a brief discussion is included on the connections through which FDI can generate a reduction in energy poverty on the continent.

¹Emna Kanzari, Samir Abdelhafidh, Stefano Fricano (2024). Chinese FDI in Sub-Saharan Africa: a new evidence of their positive effects on poverty reduction. Under review by *Economic Analysis and Policy*. Presented at XVII International Conference: Economic policies and resilience to shocks.

²Emna Kanzari, Stefano Fricano, Gioacchino Fazio, Jing Yu (2024). "Foreign Direct Investment (FDI) Impacts on Energy Poverty in African Countries". *IAEE Energy Forum*. International Association for Energy Economics. Pages: 49-53.

3.1 The state of the art of FDI and energy poverty

3.1.1 Energy poverty in Africa

Energy poverty is one of the serious challenges that the international energy system faces. It refers to a situation where households lack access to adequate, reliable, and affordable energy services, which are necessary for meeting basic needs and fostering socio-economic development (Villalobos et al., 2021). This issue results from a combination of socio-economic factors, including limited financial resources, low technological advancement, restricted physical availability of certain energy resources, inadequate infrastructure and high production costs (Njiru and Letema, 2018). As a result, energy poverty not only hinders progress toward sustainable development but also spreads inequalities. It leads to poverty, hunger, poor health and low quality of education, and it hinders innovation, industry and infrastructure development. These effects further widen existing inequality gaps, creating a cycle of deprivation that disproportionately impacts vulnerable populations. Hence, access to modern, reliable and affordable energy services offers more socio-economic opportunities by enhancing the use of basic and advanced electronic devices for example, which are necessary for extending daily activities during the night and improving the quality of education, health and work (Sambodo and Novandra, 2019).

Despite its relevance, access to basic energy is still lagging amid the international efforts to provide energy services for all. According to the Energy Progress Report 2023, despite that access to electricity raised globally between 2010 and 2021, there are still 675 million people around the world living without access to electricity in 2021. Most of these people are concentrated in the African continent with around 80% of this number is registered only in Sub-Saharan Africa. Due to its accelerating population growth, the sub-Saharan region is home to 567 million people lacking access to electricity, accounting for almost half of the regional population, with the highest numbers recorded in Nigeria, the Democratic Republic of the Congo and Ethiopia. On the other hand, North Africa has shown a significant decrease in its access deficit with a regional access rate of 94% (World Bank, 2023).

Paradoxically, Africa is known for holding almost all types of natural and mineral resources, both renewables and non-renewables that are more than sufficient to meet its domestic needs. According to the United Nations Environment Programme, around 30% of the world's mineral reserves, 12% of the world's oil and 8% of the global natural gas are registered in the continent (UNEP, 2024). In addition, Africa is home to a high and diversified potential of renewable resources including solar, wind, hydropower and bio-energies which are fundamental to providing clean and modern energy for its population.

3.1.2 FDI in Africa

The natural resources sector not only can enable the continent to cover its needs for energy but also is one of the main drivers that can play a vital role in attracting foreign investors. In fact, like many developing regions, Africa has become recently one of the most attractive destinations for foreign investments due to its vast natural resources and also for being a growing consumer market ([Gong et al., 2023](#)).

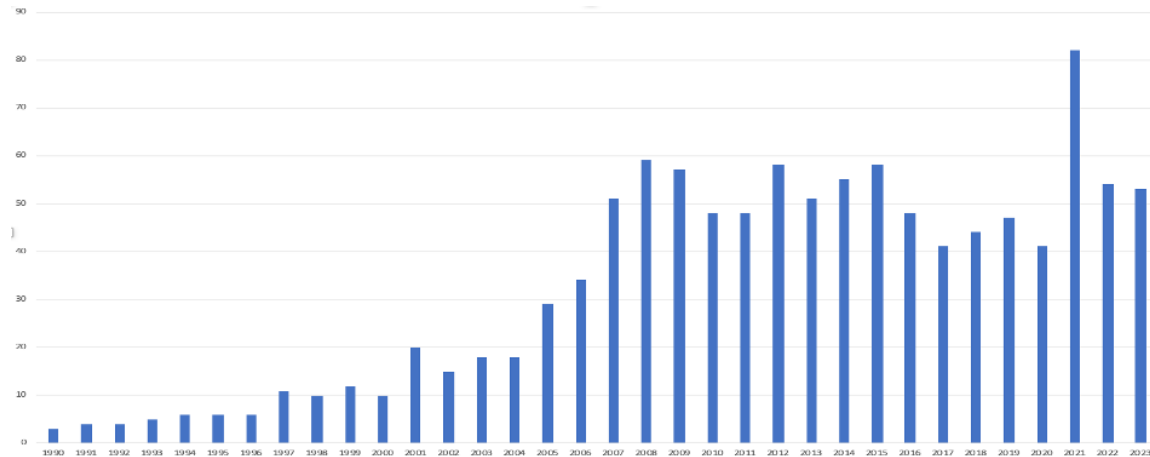
It is commonly understood that FDI is beneficial for host economies by boosting their economic growth, employment level (by creating new job opportunities), domestic investment, infrastructure, human capital development and productivity through technology and knowledge transfer ([Zhang, 2021](#)). In addition, FDI can contribute to ending poverty and its forms including energy poverty which can be reduced by increasing electricity generation access by investing directly in power generation and infrastructure ([Aluko et al., 2023](#)). FDI can bring new technologies to local firms and transfer to them new knowledge. By imitating technologies and know-how from foreign firms and taking advantage of their expertise, local enterprises learn new ways to generate electricity and thus increase electricity access ([Hu et al. \(2021\); Aluko et al. \(2023\)](#)). Accordingly, foreign capital has a strong influence on electricity access levels in hosting countries ([Aluko et al., 2023](#)).

According to the United Nations Conference on Trade and Development UNCTAD statistics, the foreign direct investment inflows to Africa have seen a tremendous increase from nearly 5\$ billion between 1991 and 1995 to around 53.5\$ billion between 2018 and 2023 (see Figure 3.1). To date, an important part of these investments is mainly received from five countries namely France, the United Kingdom, the Netherlands, the United States and China. Despite that Western countries such as France and the United Kingdom have been for a long time the first investors in Africa, China has become its leading trading and investment partner, increasing its stock by more than 50% from 2013 to 2017 and surpassing some Western partners ([Hu et al., 2021](#)).

In 2016, China topped the list of all foreign investors in the continent, which highlights the Chinese interest in investing in Africa. According to the China Statistical Yearbook, the Chinese FDI stock in Africa reached \$40.9 billion in 2022 and almost 90% of total Chinese outwards were destined for Sub-Saharan Africa between 2003 and 2022 (see Figure 3.2). Like its Western partners, China's focus has been for a long time on the natural resource extractions sector, which has been the top recipient sector for years and in 2015, it accounted for 27.5% of the total Chinese FDI in the continent. After 2015, the construction sector has gained more importance and has topped all recipient sectors. In 2022, the construction for infrastructure sector received the highest share of Chinese FDI, representing 33.3% of total China's investment stock ([CARI, 2024](#)). In recent years, Chinese firms have heavily invested in electricity and transport sectors mainly in ports and roads construction and maintenance,

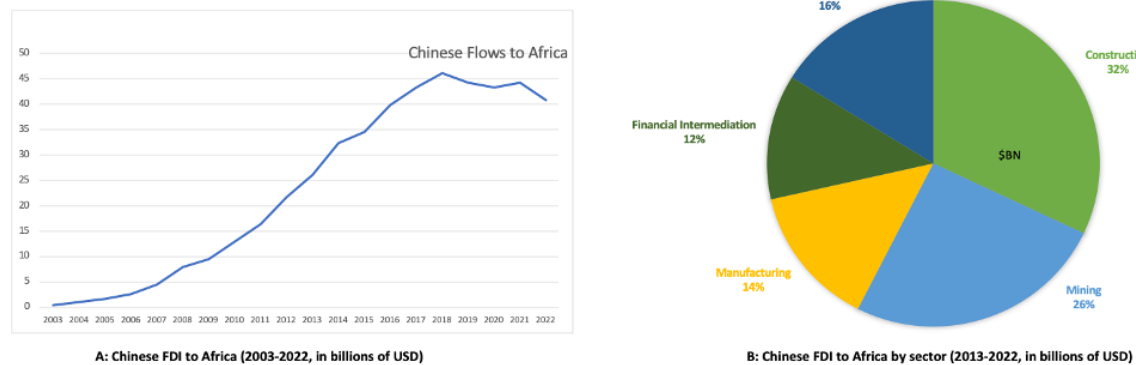
hydropower stations, power grids, hospitals and other activities such as the nuclear power project in Kenya, the first modern tramway in Sub-Saharan Africa, in addition to Tazara railways linking Zambia with the Dar es Salam port in Tanzania (Akinshipe and Aigbavboa, 2022).

Figure 3.1: FDI flows to Africa (1990-2023, in billions of USD)



Source: Authors elaboration.

Figure 3.2: Chinese FDI flows to Africa



Source: Authors elaboration.

3.2 Literature review

Access to electricity has been deeply investigated by scholars recently giving its importance in achieving a sustainable development agenda and also for its contribution in eradicating the number of people living without access to electricity specifically in the African continent. Although various studies on the drivers to eradicate energy poverty in different regions

are available, it is observed that the existing literature mainly focuses on how electricity access can be affected by economic growth, urbanization, governance, public spending, urbanisation and industrialisation. Moreover, the relationship between electricity access and FDI is underexplored with only a few previous analyses found on the topic. As for a specific FDI such as Chinese FDI, previous research is scarce, and to the best of available knowledge, there is no single work that focuses on this relationship in Africa exclusively. Multinational firms can increase electricity connectivity through different channels as evidenced in Figure 3.3. Firstly, they can raise energy access by developing and modernising electricity infrastructure since it is necessary for the investors' activities and thus expand energy generation. Foreign investors can directly develop infrastructure and new grids to provide the energy needed to facilitate their business activities (D'Amelio et al., 2016). In addition, FDI can bring new technologies to local firms and transfer to them new knowledge. By imitating technologies and know-how from foreign firms and taking advantage of their expertise, local enterprises learn new ways to generate electricity and thus increase electricity access (Hu et al. (2021); Aluko et al. (2023)). Accordingly, foreign capital has a strong influence on electricity access levels in hosting countries (Aluko et al., 2023).

D'Amelio et al. (2016) has investigated how FDI and multinational firms from 83 countries could promote electricity access in 15 host countries in Sub-Saharan Africa between 2005 and 2011. Relying on different econometric techniques mainly the system Generalised Method of Moments GMM and Least Square Dummy Variable, they concluded that the presence of FDI increases electricity access, in particular, in countries characterised by weak institutional quality. According to their analyses, FDI is associated with the development of electricity infrastructure that is necessary for their operations which also helps them gain legitimacy with the stockholders in the local economies. Similar conclusions were found by Garrone et al. (2019) in their study on the effects of multinational enterprises on energy poverty in developing countries, specifically in Sub-Saharan Africa. The authors applied the system GMM to a sample of 73 investing countries and 15 host Sub-Saharan countries over the period 2005- 2011. Their empirical results pointed out that the host countries affected by poor institutional framework have seen their electrification levels positively impacted by FDI coming from countries that are institutionally closer to them. Nguea et al. (2022) have extended the analyses on the relationship between foreign capital and electricity access of the local population to more African countries and a longer period (2000-2017), using the same technique, the system GMM which is suitable for panel data analyses. The findings reveal that while foreign aid decreases electricity access in Africa, FDI increases the share of the population that has access to electrification. However, these inflows do not seem to have a positive impact on reducing the urban-rural disparities in electricity access. More recent work on the same relationship which is conducted by Aluko

[et al. \(2023\)](#) emphasised the importance of FDI in lighting up African countries between 2000 and 2017. Not only, but they also highlighted how the interaction between governance and FDI could influence electricity access in the studied countries. Mainly, FDI has a higher effect on the level of electrification in countries with lower levels of governance.

In an attempt to study the drivers of energy poverty reduction and specifically the role of natural resources in Sub-Saharan Africa, [Nkoa et al. \(2023\)](#) employed the pooled Ordinary Least Squares (OLS) and the difference GMM on a sample of 45 African countries between 1997 and 2018. Their conclusions showed that natural resources do not increase electricity access, while per capita income, secondary education and employment help in reducing energy poverty by increasing electricity access to the local people. FDI also plays a vital role in providing electricity in Africa, particularly in rural areas. Employing different determinants including FDI in their analyses, [Khan and Majeed \(2023\)](#) focused on the financial sector development impact on energy poverty in developing countries. To empirically investigate the relationship between the different variables, they used several econometric methods such as pooled OLS, fixed and random effects and GMM. They concluded that financial development is important to alleviate energy poverty in the 110 studied economies between 1990 and 2020. The same positive impact was also found between FDI inflows and electricity access. According to the authors, foreign capitals are accompanied by advanced technology transfer that may reduce energy intensity and thus decrease energy poverty. Considering a more comprehensive financial framework, [Ajebe \(2024\)](#) examined the nexus between financial resources, energy poverty and CO₂ emissions in 54 African countries. The study contributes to the literature on the relationship between FDI and energy poverty and found out that FDI, together with financial development and official development assistance, plays a significant role in the energy landscape in Africa and has a strong connection between them, energy poverty and GHG emissions.

The other channel through which FDI can contribute to energy poverty reduction is economic growth. It is agreed that FDI is an important driver for economic development through the transmission of capital and funds, access to new markets, expansion of production and technology transfer ([Sunde, 2017](#)). Moreover, higher economic growth is generally associated with higher government spending on energy infrastructure in different areas. In addition, economic growth may result in an improvement in income levels, and thus householders are likely to choose cleaner and sustainable sources of energy. Hence, FDI can promote access to energy through its effect on economic growth ([Nguyen and Su \(2022\)](#); [Nguea et al. \(2022\)](#)).

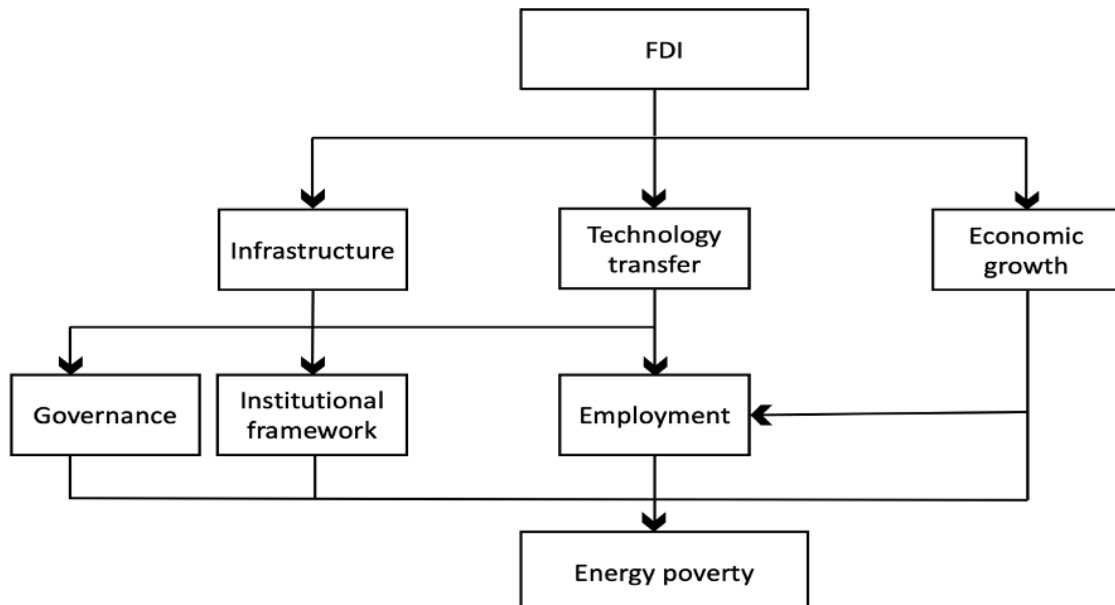
The present research aims to join the debate on the nexus between FDI and energy poverty in Africa by focusing in particular on Chinese FDI inflows to African countries instead of total FDI inflows. To the best of available knowledge, there is no previous work that has

investigated the impact of China's FDI outflows to Africa on electrification levels in the continent. The unique and very recent study that exists analyses this relationship in different countries from different regions of the 'Belt and Road Initiative' including Asia, Europe, Africa, Latin America and the Caribbean. In this study, [Zhou et al. \(2024\)](#) included a sample of 80 countries along the 'Belt and Road' from these regions over the period 2006-2018. Relying on a Spatial Durbin model (SDM), the authors confirm the vital role played by the Chinese outwards to the host countries and the alleviating energy poverty direct effect that they had. China's presence in these economies has enhanced the energy supply capacity and energy infrastructure and also the energy accessibility, cleanliness, and modernisation at the household level.

Countries like China known for being experts in infrastructure projects may positively affect host countries by transferring their knowledge and how-know to local enterprises and may help in improving the local electricity access levels for the local population. In addition, China's foreign outwards have proved to be a contributor to the African economy by enhancing its economic growth which in turn may reduce energy poverty ([Sylvaire et al., 2022](#)).

Based on what is previously mentioned, a positive relationship between Chinese FDI and electricity access in Africa is expected. In what follows, this nexus will be empirically tested to verify the hypothesis.

Figure 3.3: FDI and energy poverty nexus



3.3 Brief discussion

Considering the previous affirmations, FDI, being an importer of new technologies, able to create new job opportunities and a contributor to the host economy, represents a key driver in promoting energy access and reducing energy poverty. However, it is extremely crucial to join the debate on the FDI and energy poverty relationship, including a comprehensive empirical model to help policymakers, particularly in Africa.

The goal is to explore how African countries should structure their policies regards FDI regulations to reduce the number of people living without access to energy. This requires to carefully balance the timing of these interventions with their efficiency. Specifically, it is important to clarify the priority between addressing energy poverty in the short term or pursuing a longer-term strategy that achieves a higher percentage of people lifted out of poverty.

Moreover, policymakers must assess the relative impact of various channels through which FDI can alleviate energy poverty. Some channels may offer quicker solutions with immediate benefits, while others could require more substantial, long-term improvements. Therefore, finding an effective balance between short-term gains and long-term sustainability is essential to ensure both immediate relief and long-term progress in reducing energy poverty across Africa.

It becomes highly important to deepen the understanding of the economic processes that deeply connect different dynamics. Accordingly, further econometric analysis is needed to explore the conditions and the relations allowing to identify the balance between long-term and short-term investments. Also, it is required a deep understanding of the priorities of each territory, in order to better direct FDI.

3.4 Conclusions of Chapter 3

Understanding the relationship between foreign investments and the reduction of energy poverty in developing countries is crucial for driving sustainable progress. Foreign investments, particularly in energy infrastructure, have the potential to transform economies by providing access to clean, affordable, and reliable energy sources. This access can empower communities, improve living standards, and foster economic growth. However, the complexity of this relationship demands a deep, interdisciplinary exploration to assess both the positive impacts and the challenges that may arise.

While FDI, coming from China or other countries, represents an immense opportunity to enhance countries' socio-economic development and reduce their energy poverty levels, it is important to consider the challenges and complexities that arise from this kind of invest-

ment. First, FDI may be directed toward sectors that do not directly benefit households, such as extractive industries or industrial zones, prioritising electrification for firms over individuals. This risk threatens to perpetuate energy poverty in rural and marginalised areas. Second, FDI can increase environmental degradation, complicating Africa's efforts to mitigate climate change. Finally, the growing engagement of foreign countries like China in Africa has raised concerns about economic dependency and sovereignty. By heavily investing in certain sectors, large economies may exercise a certain power over host nations, influencing policy decisions and fostering neo-colonial dynamics that prioritise foreign interests over local needs.

A **call for research** is being proposed to establish a network of complementary studies aimed at collectively addressing the multifaceted connections between foreign investments and the reduction of energy poverty. By gathering diverse perspectives—spanning fields such as economics, environmental science, policy analysis, and social justice—this initiative seeks to create a comprehensive body of work.

The proposed goal is to compile these studies into a unified framework that, like pieces of a puzzle, will offer a clear and holistic understanding of how international funding can effectively combat energy poverty. This initiative will invite scholars and experts to contribute their research and insights, fostering collaboration across disciplines. The outcome of this collective effort is envisioned to inform and guide future policy-making and investment strategies, ultimately promoting equitable and sustainable development in regions most affected by energy poverty.

Conclusions

This thesis has examined the dynamics of energy transition in Africa, with a particular focus on the role of renewable energy in ensuring sustainable development. The different chapters discussed, in particular, the energy landscape of certain African countries, the factors influencing their energy transition and the role of renewable technologies in promoting specific Sustainable Development Goals (SDGs). This was followed by further emphasis on the concept of energy security, exploring how renewable energy implementation can contribute to a sustainable and secure energy system in Africa. The analysis was not limited to African countries but included a comparative analysis to discuss the energy security dynamics from a global view. The last part of the thesis was destined for a specific dimension of energy security for African nations. Given the continent's vulnerability to energy supply disruptions, the research examined energy poverty, concentrating specifically on the role of Chinese Foreign Direct Investment in mitigating energy poverty.

The thesis tried to discuss energy and development issues, presenting the main literature review and using different statistical and econometric approaches and different reliable datasets including energy, socio-economic, political and environmental variables. Finally, the results of each chapter offered some specific policy recommendations to be considered by policymakers working on the related subjects.

The findings of the first chapter highlighted that African countries are heterogeneous in their approach to energy transition, as demonstrated by the cluster analysis conducted on 25 countries over the period 2000-2020 (see Chapter 1). The clustering technique revealed four distinct groups of countries (A to D), each with its own energy characteristics shaped by a combination of socioeconomic, political, and environmental factors. However, each cluster obtained requires tailored strategies aligned with specific SDGs. For instance, Cluster A needs policies promoting renewable energy adoption and democratic stability (SDG 7 and SDG 16). Cluster B requires targeted interventions to promote economic diversification and reduce inequalities (SDG 10). Cluster C demands strategies leveraging renewable energy and enhancing governance (SDG 9 and SDG 16). Finally, Cluster D necessitates transitioning to cleaner energy sources to combat climate change (SDG 7 and SDG 13).

Chapter 2 aimed to explore how greater use of renewables may influence energy security through its effects on energy stock changes. The results highlight that an increase in renewable production induces countries to keep low energy stocks, suggesting that countries with significant renewable production have less energy security risks. The findings also suggest that when a country is heavily engaged in international markets, it is likely to be more sensitive to any change in market factors. First, if a country is an important importer of energy, it may be highly affected by any supply disruption or price variation and tends to

maintain high stocks of energy. In this case, diversifying their energy system by employing more renewable resources will provide more alternatives and help in gaining energy security. Secondly, similar to importers, exporters of energy accumulate energy reserves to benefit from any price rise on the market by selling them at higher prices.

The balance between keeping high stocks or reducing them remains complicated for certain countries. Renewable energy can represent a great opportunity to gain energy security, and countries should accelerate their investments towards their use, which will facilitate the energy transition goal. Investing in renewables will lead to decreased energy stocks since the focus is shifted from investing in fossil energy to clean energy. At the same time, these countries face a serious challenge, when deciding whether to continue with fossil fuel production and take advantage of storing energy or to shift towards greater renewable sources. When countries decide to maintain high stocks to ensure energy stability, they freeze a significant portion of their capital to produce and maintain these reserves. On the other hand, when countries have enhanced renewable production, the capital destined to maintain energy stocks becomes available to be invested in additional development projects, offering economic and social benefits and higher government spending on public services. Therefore, it is highly recommended for these countries to carefully evaluate their short-term needs and long-term sustainability goals to better design their energy policies.

Furthermore, the development of renewable energy infrastructure can significantly enhance the quality of life in African countries. Renewable projects create jobs, stimulate local economies, and provide reliable electricity to communities that may currently lack access. For example, solar power installations can bring electricity to rural areas, enabling residents to access modern amenities, improve educational opportunities, and support local businesses. Wind and hydroelectric projects can also contribute to a more diversified and resilient energy system, reducing the risk of supply disruptions.

Investing in the energy sector is crucial for Africa's development as it is beneficial to its energy system and also to its population's standard of living. However, due to their financial limits, some countries need to rely on foreign financing and foreign investments to improve their socioeconomic growth, which increases with the increase of electricity access. The last chapter takes into account this particular aspect. The work focused on the role played by Chinese firms in facilitating access to electricity in investment-receiving countries. The analysis highlighted that Foreign Direct Investment (FDI) can reduce energy poverty through different channels mainly by directly increasing investments in the energy sector, bringing technological transfer to the local firms, positively impacting economic growth and creating new jobs for many Africans. Therefore, FDI is a fundamental tool for these countries to fight energy poverty, particularly those coming from the most technologically advanced countries such as China. It is important for African countries to

attract these inflows and consider them in their national policies. In particular, it is highly recommended to evaluate these channels in more detail and understand which of them can offer quicker and more efficient outcomes. This interaction between FDI and the different channels together with energy poverty (electricity access) needs more in-depth analysis. The first step in further work is to discuss these points, considering an empirical model that allows the study of these connections and including other possible interactions.

Not only that but future research can touch other aspects related to the themes discussed in this thesis. The field of energy transition from an economic point of view is vast and the literature gap is still significant. The different analyses in this thesis tried to fill some gaps and also presented new and innovative research regarding energy dynamics in developing and developed countries. However, it could be interesting to stretch further the analysis and study renewable energy technologies separately, focus on each specific technology and compare them for African countries and even for extended countries. Future analyses can also include specific case studies with a particular focus on one single country rather than another. This would offer a detailed understanding of the country-specific context and its challenges, contributing to their national policy framework. The thesis observations provided some insights into the energy scene in African countries and put into evidence the importance of renewable resources in shifting the continent's energy future. Therefore, these findings can represent a starting point for building further conclusions and drawing further specific policy recommendations in the studied regions.

.1 Appendix A

Table 1: Summary of the variables included in the analysis

Variables	Description	Source
RE production	The RE production, expressed in Terajoule (TJ).	International Energy Agency (IEA)*
RE consumption	The RE consumption, expressed in TJ.	International Energy Agency (IEA)*
Fossil fuels production	Fossil fuels production expressed in TJ.	International Energy Agency (IEA)*
Fossil fuels consumption	Fossil fuels consumption expressed in TJ.	International Energy Agency (IEA)*
Fossil fuels imports	Fossil fuels imports expressed in TJ.	International Energy Agency (IEA)*
GDP per capita	Gross Domestic Product per capita expressed in current US\$.	World Development Indicators**
Foreign Direct Investment	Foreign Direct Investment expressed in current US\$.	World Development Indicators**
Trade openness	Imports and exports of goods and services, expressed as % of GDP.	World Development Indicators**
Political stability	Political stability and absence of violence/ terrorism (from -2.5 to 2.5).	World Development Indicators**
Level of democracy	The level of democracy index ranging from 0 to 100.	Freedom House***
WESII	World Economic and Social Impact Index (from 0 to 100).	World Economics****
CO2 emissions	Carbon dioxide emission, expressed in kiloton (kt).	World Development Indicators**

Notes: *Bought from the International Energy Agency, *World Energy Balances*. [IEA \(2023b\)](#).
 *** The World Bank Group 2023. *DataBank, World Development Indicators* [World Bank \(2023\)](#).
 **** Freedom House website [Freedom House \(2023\)](#).
 ***** World Economics website [World Economics \(2023\)](#).

Table 2: The means of each energy variable for each country 2000-2020.

Country	RE consumpt*	RE prod- uct*	FF consumpt*	FF product*	FF imports
Algeria	1543.98* (1070.72)**	2874.59 (923.46)	1048483.45 (340290.84)	3118264.61 (243909.11)	100505.95 (62690.58)
Angola	179663.84 (17056.79)	252745.48 (33464.39)	152249.65 (54654.73)	3108107.74 (822070.41)	117214.02 (71296.63)
Botswana	20666.24 (1860.97)	21787.72 (830.80)	39724.18 (4587.23)	31582.71 (13374.87)	36275.61 (5915.81)
Cameroon	210878.89 (24159.64)	248794.93 (38115.65)	50027.58 (10270.27)	196932.71 (32551.94)	80744.66 (13481.15)
Congo	34681.63 (16916)	48032.44 (19867.89)	19041.28 (7424.49)	593269.59 (84965)	7636.1 (5201.18)
DR Congo	711924.78 (96132.52)	907407.44 (256352.12)	26327.27 (13083.61)	49667.17 (3767.65)	31711.26 (14320.89)
Cote d'Ivoire	169954.93 (33795.31)	273501.04 (47329.18)	65506.85 (20973.99)	128242.65 (31191.16)	147416.52 (16261.88)
Egypt	674.37 (2913.45)	1834.92 (16794)	42526.09 (279787.51)	708790 (477243.35)	9725.88 (377288.14)
EqGuinea	62229.69 (39.05)	188519.4 (840.62)	1568700.76 (18010.51)	3066723.57 (205584.74)	578800.56 (2223.74)
Eswatini	22378.19 (2503.97)	28010.73 (3938.7)	4236.23 (881.53)	7808.1 (3798.87)	8345.57 (1283.01)
Gabon	122028.7 (43457.98)	125529.02 (43562.76)	20496.76 (8273.76)	516063.72 (42564.64)	12492.93 (6755.24)
Ghana	112656.41 (10687.01)	170919.72 (17867.61)	112028.96 (38502.81)	146523.62 (164675.65)	167564.48 (47773.05)
Libya	9746.17 (1126.32)	21998.18 (4063.66)	352203.64 (44613.03)	3083832.85 (1114984.91)	-6636.08 (123050.62)
Morocco	59582.51 (13391.83)	73298.91 (12284.05)	394510.72 (88334.47)	2691.52 (585.40)	683796.66 (134975.71)
Mozambique	217249.55 (37549.07)	336844.55 (28350.17)	43520.42 (19387.54)	207765.99 (183023.07)	-48844.26 (39256.78)
Niger	73465.08 (19719.84)	75596.51 (19744.92)	13624.67 (5977.70)	17810 (18099.81)	8288.97 (3647.48)
Nigeria	3764517.02 (605918.72)	4068834.51 (700438.15)	723081.04 (209978.91)	5861826.69 (488768.58)	551739.41 (267455.35)
Senegal	39913.61 (9712.69)	66081.54 (14518.70)	47019.71 (10474.72)	687.77 (446.58)	103006.11 (27969.57)

South Africa	224544.09 (40667.51)	343001.57 (54084.19)	1680958.2 (193514.91)	5935617.6 (266276.73)	1188898.94 (213264.15)
Sudan	276239.9 (15413.94)	495014.26 (27077.03)	150710.13 (49998.68)	519008.63 (317511.45)	52920.71 (32105.54)
Tanzania	597972.3 (71822.73)	683319.59 (86438.91)	73458.04 (29256.33)	161491.39 (26536.44)	77875.82 (27167.84)
Tunisia	37707.3 (2902.59)	47914 (3730.79)	212083.41 (25987.55)	230796.48 (39628.99)	270000.74 (48828.82)
Zambia	204597.25 (26027.76)	307959.05 (41242.28)	39117.14 (14524.53)	7271.97 (9266.08)	41651.05 (15196.98)
Zimbabwe	273033.2 (27711.10)	293529.48 (28007.46)	62159.01 (10226.72)	87881.06 (27484.45)	42963.24 (12724.89)

Notes: *each value refers to the mean of each variable for each country.

* ** values in () refer to the standard deviation of each variable for each country.

Consumpt*: consumption; Produt*: production; FF: Fossil fuels.

Table 3: The means/ last available values of each variable for each country between 2000-2020.

Country	[1]*	[2]*	[3]**	[4]*	[5]*	[6]*	[7]**
Algeria	3808.73	-1.19	32	121781.5	1425623435.44	63.21	73.9
Angola	2637.04	-0.63	28	21571.34	-426503104.16	94.23	30.6
Botswana	5512.55	1.03	72	5052.18	279514884.36	95.4	58.8
Cameroon	1300.38	-0.75	15	7033.89	473507100.96	46.04	41.4
Congo	2235.13	-0.72	17	4953.2	1109528187.8	123.68	39
DR Congo	356.08	-2.12	19	2655.77	1082943114.87	61.22	21.1
Cote d'Ivoire	1656.63	-1.41	49	7648.7	440249011.67	56.53	44.2
Egypt	2233.9	-0.99	5	189485.25	5239719047.62	46.66	70.4
EqGuinea	10403.65	-0.03	18	5050.73	675645152.22	112.71	70.4
Eswatini	3214.78	-0.22	17	1017.37	51116575.94	111.37	35.3
Gabon	7132.09	0.19	20	5723.2	682393638.34	82.77	65.7
Ghana	1280.27	0.01	80	10892.84	2008520287.68	79.4	56.7
Libya	9236.53	-0.9	10	51476.51	849395238.1	79.3	68.2
Morocco	2789.06	-0.39	37	51661.09	2218665800.9	67.23	65.2
Mozambique	483.71	-0.13	45	3742.02	2082407515.92	82.15	16.3
Niger	424.57	-0.85	51	1378.77	388374953.6	40.02	25
Nigeria	1883.2	-1.91	43	99958.39	4157008567.37	36.51	31.1
Senegal	1186.06	-0.19	68	7358.39	421913168.19	56.50	70.50
South Africa	6052.51	-0.12	79	398484.34	4217243833.81	53.27	65.1
Sudan	1374.78	-2.14	10	14850.33	1352915116.91	26.07	65.4

Tanzania	725.94	-0.37	36	7993.44	997721990.74	39	38.1
Tunisia	3529.07	-0.34	56	26822.05	1091342027.21	94.25	69.6
Zambia	1133.3	0.23	54	3795.44	854175823.79	69.18	31.4
Zimbabwe	965.75	-0.99	28	10634.53	203019692.41	69.03	41.9
Total	71555.7	-14.94	889	1061021.26	31876441061.67	1685.73	1195.3

*Note: * indicates the mean calculated from 2000 to 2020 while ** refers to the last available year. [1]: GDP/capita ; [2]: Political Stability; [3]: Democracy level; [4]: CO2 emissions; [5]: FDI; [6]: Trade; [7]: WESII.*

Table 4: Correlation matrix

Variables	GDP/ capita	Political Stability	Democracy level	CO2 emis- sions	FDI	Trade	WESII
GDP/capita	1						
Political Stability	0.348	1					
Democracy level	-0.145	0.468	1				
CO2 emissions	0.234	-0.044	0.208	1			
FDI	-0.022	-0.196	0.084	0.742	1		
Trade	0.449	0.521	-0.057	-0.274	-0.376	1	
WESII	0.587	0.186	0.027	0.343	0.201	0.031	1

Table 5: Means of each socio-economic and political variable by cluster.

Cluster	GDP/ capita	Political Stability	Democracy level	CO2 emissions	FDI	Trade	WESII
A	4181.04	-0.80	18.8	14301.48	5.7E+8	80.74	46.44
B	1142.89	-0.37	43.67	5299.36	1.15E+9	73.41	34.97
C	2847.80	-0.89	34.78	42304.29	1.55E+9	62.49	54.48
D	4540.71	-0.17	55	144244.78	2.04E+9	69.78	65.75

Table 6: Means of each energy variable for each African country, 1992-2020

Country	Stock changes	RE production	Production	Consumption	Imports	Exports
Algeria	46.49	2750.72	5919141.33	1016568.42	85719.99	4376885.95
Angola	-803.98	238866.81	2865453.54	312248.56	87412.84	2518704.83
Benin	333.37	83835.62	84879.57	112403.89	53810.97	7143.83
EqGuinea	1270.05	1605.29	531592.50	33328.14	7533.95	531168.54
Ethiopia	3454.88	1202462.27	1202543.93	1215537.30	97784.22	7871.27
Gabon	-1760.39	101404.76	673832.02	121763.18	10700.01	544427.98
Morocco	-7667.71	67502.48	74513.13	477417.54	608124.08	31940.43
Mozambique	-3592.27	313627.45	464281.04	275151.76	57829.87	165589.21
Nigeria	1145.92	3658814.56	9180690.71	4102596.08	414217.39	4905952.49
South Africa	-9507.28	384497.92	6188498.91	2495499.86	1090025.48	2099637.48
Tunisia	1883.36	43672.81	273847.32	268017.57	241076.54	144807.01
Zambia	-879.18	284015.26	290695.37	254119.61	37578.09	3912.86
Zimbabwe	-2998.55	274861.93	374043.43	360169.47	56968.28	6961.02

Table 7: Descriptive statistics of the global sample (1992-2020)

Variable	Mean	Std. dev.	Min	Max
Stock changes	1.39e+03	6.00e+04	-2.99e+05	5.06e+05
RE production	3.15e+05	3.08e+05	6.47e+03	1.89e+06
Energy production	2.21e+06	2.64e+06	5.32e+04	1.18e+07
Energy consumption	2.42e+06	2.45e+06	3.18e+05	1.01e+07
Energy imports	2.73e+06	2.82e+06	1.89e+05	1.12e+07
Energy exports	1.32e+06	1.98e+06	8.99e+03	3.28e+04
GDP growth	1.9	3.1	-11.3	24.4

Table 8: Means of each energy variable for each European country, 1992-2020

Country	Stock changes	RE production	Production	Consumption	Imports	Exports
Germany	35533.24	889759.80	5631431.57	9616169.22	9964868.57	1511259.90
UK	32111.97	223079.62	8019592.47	5807995.05	4881078.31	3885570.34
France	-11157.87	782264.38	5473429.82	6563809.61	6554297.00	1229611.23
Italy	-3172.76	628411.99	1304292.75	5246566.60	6784612.46	1068024.79
Spain	-1470.39	451452.99	1370295.01	3455625.24	4661820.36	690293.11
Netherlands	-10158.01	110159.18	2502314.30	2477465.78	6216008.06	4903683.55
Switzerland	5454.36	186301.86	493938.67	801591.57	739525.93	131700.77
Poland	-22646.66	243028.85	3317894.88	2745054.45	1611228.10	796306.88
Sweden	-975.15	618617.40	1387885.65	1422507.98	1325529.89	552312.85
Belgium	-2810.82	63726.51	571013.93	1663156.63	3168257.77	1118945.44
Norway	-5813.92	503857.47	8474639.51	831533.29	294733.26	7584920.65
Ireland	154.88	22268.14	110821.51	430105.84	521790.81	56365.67
Austria	-490.87	314649.08	434727.35	1052063.49	1103656.98	226950.78
Denmark	686.72	99858.92	836706.95	595417.28	682594.19	678043.20
Romania	686.72	186934.47	1209539.53	622981.56	622981.56	190878.44
Finland	13481.56	348173.19	665241.38	1028966.93	1010840.60	269816.70
Czech	3663.24	112152.82	1345075.91	1134482.02	835274.10	357424.49
Portugal	-39.65	182488.86	186882.37	722629.43	961445.60	160392.93
Greece	-1511.89	76185.11	381334.85	736263.40	1215049.63	384446.08
Hungary	-5629.39	76032.36	499688.54	776817.49	772270.39	167677.61

Table 9: Descriptive statistics of the global sample (1992-2020)

Variable	Obs	Mean	Std. dev.	Min	Max
Stock Changes	1368	-	279069.5	-	2910157
		7949.73		3497021	
RE production	1392	1160894	2677514	37.99	1.92e+07
Energy production	1392	9097611	2.22e+07	950.40	1.57e+08
Energy consumption	1392	6340743	1.54e+07	1486.10	1.00e+08
Energy imports	1390	3446347	6777768	21.00	4.79e+07
Energy exports	1390	3115249	6201368	44.68	5.19e+07
GDP growth	1383	3.160286	6.34738	-23.98	149.97

Table 10: Means of the energy variables by country for the global sample (1992-2020)

Country	Stock Changes	RE production	Production	Consumption	Imports	Exports
Algeria	1613.9	2750.7	5919141.3	1016568.4	85720	4376886
Angola	-1520.9	238866.8	2865453.5	312248.6	87412.8	2518704.8
Argentina	-6610.3	234109.7	3168248.9	2006288.5	341919.6	609298.9
Australia	-18544.9	290315	12029816.9	3058351	1484703.2	8538531.6
Austria	-729.3	321716.3	440860.1	1065386	1125201.6	239065.4
Belgium	-2763.9	66723.9	572748.7	1682086.4	3206901.6	1134911.2
Brazil	172.4	4090163	8553620.5	7600240.1	2430059.4	1201373.8
Canada	102314.5	1864157.1	17252422.5	7878508.4	3149907.2	9429924.7
Chile	-6381.1	324677.9	426094.5	913893.3	868507	36621.9
China	-299560.2	9742720.3	74300469.8	55949405.2	13107777.7	2681432.9
Colombia	70250.4	338610.8	3867485.5	1000260.3	121965.8	2695346
Czech	3188.9	116588.6	1322076.4	1122841.3	838090.8	348535.6
Denmark	2716.6	103631.1	862650.3	597305.6	681464.1	700964.8
Ecuador	13612.9	64209.5	1093071.2	360179.9	152500.2	764658.8
EqGuinea	597	1605.3	531592.5	33328.1	7533.9	531168.5
Finland	12949.6	357264.8	677553.7	1035739.6	1023504.1	281390.8
France	-5965.9	789481.6	5518278	6592641.1	6593697.5	1255751.5
Germany	29590.2	936132.5	5508075.9	9588173.3	10092873.6	1559421.1
Greece	-2049.2	78069.1	381309.3	744735.9	1236073.8	392730.7
Hungary	-6845.5	78985.8	492091.7	772444.2	782562.6	174952.6
India	-97928.7	6549129.6	17251036.7	16401378	8638885.7	1516389.9
Indonesia	-4706.6	2482940.2	13386481.9	5466039.2	1531092.3	7434528.7
Iran	20905	56675.6	12505698.9	5604378.6	452434.7	5523302.5

Ireland	319.4	23319.5	108712.4	437786	535498.5	58175.6
Italy	-3344.9	651892.5	1320038	5272914.7	6829399.4	1085003.1
Japan	11918.7	739970.2	3221872.7	13130051.9	17688037.5	537737.2
Kenya	-3154.7	624177.9	624177.9	500578.1	173669.3	9515.5
Korea	-45499.4	82780.9	1606011.5	5942087.8	9706616.4	1785949.1
Mexico	-3807.8	668559.3	9027080.8	4387834.1	1808777.2	3677991.1
Morocco	-7257.7	67502.5	74513.1	477417.5	608124.1	31940.4
Netherlands	-10881.6	115587.8	2490074.9	2489790.1	6348328.2	4994601.7
Nigeria	1097.3	3658814.6	9180690.7	4102596.1	414217.4	4905952.5
Norway	-3922.7	507154.9	8696792.6	838838.5	299840	7796999.3
Peru	-11297.5	204772.7	670987.4	580360.1	287790	233632.4
Poland	-23217.7	255549	3252608.9	2756557.3	1658273	790180
Portugal	895.7	185602.4	189972.8	733623.4	977561.5	164241.7
Qatar	-2582.8	64.8	5223011.2	488570.5	6938.7	4226617
Romania	-404.3	194696.9	1183080.6	1047273.5	601815.8	192692.7
Russia	-200646.8	802651.3	49841739	18836021.2	1100762.8	21887940.4
Southafrica	-24069.7	384497.9	6188498.9	2495499.9	1090025.5	2099637.5
Spain	-2847	464750.1	1365232.8	3514400.2	4767032.8	700074.6
Sweden	-2309.2	628762.4	1395382.6	1427793.7	1337256.6	562786.9
Swizertland	5443.3	188480.5	498259	802843.7	740441.7	134115.9
Thailand	11023.7	830877.4	2360808.8	2975987.5	2358508.8	386520.8
Tunisia	2774.5	43672.8	273847.3	268017.6	241076.5	144807
Turkey	-12022.3	523758.8	1241255.7	2996053.6	3079013.2	218528
UK	37887.9	235513.1	7962326.4	5801259.4	4969100.7	3927814.9
USA	100839.2	14509997.8	129762051.1	91249099.7	39518545.7	34854372

Table 11: Descriptive statistics for lesser-developed countries (1992-2020)

Variable	Obs	Mean	Std. dev.	Min	Max
Stock Changes (TJ)	862	4.248e+04	9.279e+05	-7.951e+05	1.97e+07
RE production (TJ)	899	7.965e+05	1.475e+06	9.26e+02	9.274e+06
Energy production (TJ)	899	2.684e+06	4.322e+06	9.504e+02	2.42e+07
Energy consumption (TJ)	899	1.696e+06	3.369e+06	1.486e+03	2.60e+07
Energy imports (TJ)	899	6.979e+05	1.885e+06	1.058e+03	1.83e+07
Energy exports (TJ)	867	2.428e+04	2.146e+06	-6.008e+06	1.22e+07
GDP growth (%)	899	4.435e+00	7.47e+00	-2.398e+01	1.4997e+02

Table 12: Means of the energy variables by country for the lesser-developed countries (1992-2020)

Country	Stock Changes	Re prod*	EP**	EC***	Imports	Exports
Algeria	1.61386e+3	2.62565e+3	5.91914e+6	1.01657e+6	8.57200e+4	4.37689e+6
Angola	-1.52087e+3	2.30095e+5	2.86545e+6	3.12249e+5	8.74128e+4	2.51870e+6
Benin	2.76100e+1	7.99647e+4	8.48796e+4	1.12404e+5	5.38110e+4	7.14383e+3
Bolivia	3.07860e+2	4.48634e+4	5.46513e+5	1.80687e+5	2.51771e+4	3.26217e+5
Brazil	1.72410e+2	4.09016e+6	8.55362e+6	7.60024e+6	2.43006e+6	1.20137e+6
Colombia	7.02504e+4	3.38611e+5	3.86749e+6	1.00026e+6	1.21966e+5	2.69535e+6
Ecuador	1.36129e+4	6.42096e+4	1.09307e+6	3.60180e+5	1.52500e+5	7.64659e+5
EqGuinea	5.96950e+2	1.45959e+3	5.31593e+5	3.33281e+4	7.53395e+3	5.31169e+5
Ethiopia	1.99301e+3	1.13517e+6	1.20254e+6	1.21554e+6	9.77842e+4	7.87127e+3
Gabon	5.17097e+3	9.29720e+4	6.73832e+5	1.21763e+5	1.07000e+4	5.44428e+5
Guatemala	-3.04765e+3	2.50180e+5	2.82703e+5	3.25744e+5	1.60423e+5	3.62255e+4
Honduras	2.19515e+3	8.76906e+4	8.76906e+4	1.47450e+5	9.44303e+4	6.42536e+3
India	-9.79288e+4	6.54913e+6	1.72510e+7	1.64014e+7	8.63889e+6	1.51639e+6
Indonesia	1.32033e+6	2.48294e+6	1.33865e+7	5.46604e+6	1.53109e+6	7.43453e+6
Jamaica	1.01317e+3	1.01711e+4	1.01711e+4	8.67955e+4	1.34052e+5	5.41588e+3
Mongolia	-1.83914e+4	6.17256e+3	4.03852e+5	1.04569e+5	3.63524e+4	2.85973e+5
Morocco	-7.25768e+3	6.49320e+4	7.45131e+4	4.77418e+5	6.08124e+5	3.19404e+4
Mozambique	-8.10813e+3	3.03528e+5	4.64281e+5	2.75152e+5	5.78299e+4	1.65589e+5
Myanmar	1.42332e+3	4.35919e+5	8.27541e+5	5.62974e+5	8.22491e+4	2.73091e+5
Nicaragua	-1.49170e+2	7.01327e+4	7.01327e+4	8.68810e+4	5.63955e+4	1.46432e+3
Nigeria	1.09728e+3	3.46746e+6	9.18069e+6	4.10260e+6	4.14217e+5	4.90595e+6
Pakistan	1.47240e+2	1.27617e+6	2.40947e+6	2.69304e+6	9.03800e+5	4.05346e+4
Peru	-1.12975e+4	2.04773e+5	6.70987e+5	5.80360e+5	2.87790e+5	2.33632e+5
Philippines	6.37928e+3	7.34448e+5	9.44766e+5	1.06825e+6	9.66011e+5	1.15336e+5
South Africa	-2.26988e+4	3.94115e+5	6.18850e+6	2.49550e+6	1.09003e+6	2.09964e+6
Sri Lanka	8.70700e+3	1.93595e+5	1.93595e+5	3.25742e+5	1.91608e+5	4.32074e+3
Thailand	1.10237e+4	8.30877e+5	2.36081e+6	2.97599e+6	2.35851e+6	3.86521e+5
Tunisia	2.77449e+3	4.20000e+4	2.73847e+5	2.68018e+5	2.41077e+5	1.44807e+5
Vietnam	-1.53154e+4	6.68376e+5	2.12295e+6	1.57517e+6	6.15392e+5	7.22218e+5
Zambia	9.26220e+2	2.72406e+5	2.90695e+5	2.54120e+5	3.75781e+4	3.91286e+3
Zimbabwe	-2.99855e+3	2.66471e+5	3.74043e+5	3.60169e+5	5.69683e+4	6.96102e+3

Notes: *: RE production. **: Energy production. ***: Energy consumption.

All variables are expressed in Terajoule TJ.

Table 13: Means of the energy variables constructed by country for lesser-developed economies (1992-2020)

Country	% of stock decrease*	REshare	EAS	EDF	ESF
Algeria	0.517	0.002	6.635	0.081	0.741
Angola	0.310	0.583	9.018	0.234	0.866
Benin	0.483	0.715	0.804	0.434	0.098
Bolivia	0.414	0.198	2.910	0.122	0.538
Brazil	0.448	0.418	1.096	0.328	0.119
Colombia	0.517	0.268	3.804	0.110	0.672
Ecuador	0.793	0.137	3.145	0.379	0.695
EqGuinea	0.793	0.112	20.244	0.419	0.930
Ethiopia	0.724	0.925	0.993	0.075	0.008
Gabon	0.517	0.719	7.632	0.086	0.802
Guatemala	0.345	0.614	0.872	0.484	0.133
Honduras	0.586	0.510	0.598	0.619	0.062
India	0.276	0.285	1.081	0.471	0.076
Indonesia	0.586	0.342	2.405	0.270	0.538
Jamaica	0.586	0.074	0.122	1.563	0.569
Mongolia	0.448	0.040	3.166	0.331	0.400
Morocco	0.345	0.109	0.166	1.270	0.450
Mozambique	0.414	0.902	1.632	0.201	0.269
Myanmar	0.483	0.707	1.449	0.124	0.281
Nicaragua	0.448	0.563	0.807	0.642	0.021
Nigeria	0.483	0.785	2.292	0.088	0.537
Pakistan	0.655	0.395	0.904	0.328	0.016
Peru	0.379	0.295	1.126	0.488	0.323
Philippine	0.621	0.418	0.880	0.893	0.112
South Africa	0.448	0.077	2.488	0.429	0.339
Sri Lanka	0.828	0.541	0.606	0.570	0.020
Thailand	0.586	0.197	0.800	0.785	0.152
Tunisia	0.448	0.120	1.070	0.892	0.529
Vietnam	0.379	0.407	1.395	0.358	0.349
Zambia	0.586	0.882	1.149	0.142	0.014
Zimbabwe	0.172	0.649	1.040	0.158	0.019

*Notes: *: the percentage of years in which there was positive numbers (indicating stock decline) in the dataset.*

.1 Appendix B

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Analysing the energy landscape in Africa using cluster analysis: Drivers of renewable energy development

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ABSTRACT

International attention toward energy transition has seen significant growth recently. Each region has focused on some of its aspects according to its own context. Our work focuses on African countries and analyses their energy transition. Our study adds to the literature on energy transition studies by understanding the energy landscape of African countries and identifying similarities and differences between them using a cluster analysis based on a multivariate Euclidean distance measure. Thanks to this measure, we highlighted four clusters. We discuss how these clusters are explained by similar economic, political and cultural factors. The cluster that uses the most RE (Green-Cluster) has low political stability and high foreign direct investment, suggesting that RE can be an opportunity to attract investors and enhance green economic development. Countries of cluster that show high FF consumption (Brown-cluster), have high CO₂ emissions but better economic and social situations. Lastly, we proposed diverse policy implications for the different clusters, offering a range of indications aimed at advancing specific Sustainable Development Goals. It is necessary to focus on developing strategies to leverage RE and enhance governance for countries of Green-Cluster. For Brown-cluster, they should accelerate the transition to cleaner energy sources to combat climate change.

1. Introduction

The significant changes that our world has been witnessing in the last century including economic growth, technological progress, population growth, industrialization and changes in individual behaviours, are the main reasons behind the increment in global energy demand. This permanently growing demand has become a prominent worry for international organizations as it was associated with the widespread adoption and use of fossil fuels (FF).

As commonly understood, FF energy is directly related to CO₂ emissions, climate change, global warming, pollution, energy price fluctuations and even geopolitical tensions (Scholten et al., 2020). Due to these serious impacts, global efforts were mainly focused on reducing global FF use and enhancing the energy transition toward modern energy sources such as solar energy, wind power, hydropower and bioenergy, which are environmentally friendly and available in abundance (Maji et al., 2019).

Renewable energy (RE) provides clean energy to mitigate environmental challenges and alternative energy to gain energy security and reduce geopolitical tensions between nations. Due to these factors, RE has become increasingly important during the last years and international organizations have considered it a fundamental factor for productive economic development, lower levels of greenhouse gas

emissions and also higher energy independence (Olanrewaju et al., 2019).

International organizations along with governments in different countries around the world have emphasized the necessity of adopting efficient RE policy reforms in each country's national plan and shifting their energy system toward renewables.

According to British Petroleum statistics, the global primary energy consumption has continued to increase reaching in 2021 the largest growth in history with 595.15 EJ. This increase was entirely explained by the expansion of RE sources which represented 17.7% of total final energy consumption in 2019. In 2021, the global RE consumption reached 39.91 EJ and it was mainly driven by solar and wind energies which accounted together for more than half of total RE consumption in the last 10 years (Li et al., 2022).

Nevertheless, the development of RE remains uneven across regions and countries. Among all the regions, Asia Pacific outpaces the rest of the regions in RE installed capacity and includes the largest amount of RE. According to British Petroleum, almost half of the RE consumed in the world was registered in this region, accounting for 17.5 EJ in 2021. Following Asia, Europe is the second largest region in terms of RE generation and consumption, which accounted for 25.9% and 25.4% of global renewables in 2021, respectively. North America and South and

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Central America by their turns represent 21.2% and 8.4% of worldwide RE, respectively, with the United States being the largest consumer and generator of renewables in North America (18.7%) and Brazil leading South and Central America (6%). As for Africa, with only 1.3% of global RE generation and 1.2% of global consumption, it is still far behind compared to different regions of the globe (BP, 2022).

Paradoxically, Africa has a great potential for renewable sources starting from rivers and water channels for hydropower, abundant sunlight for solar energy to a large wind power potential. Regardless of this vast potential, only a small part of it could be tapped in the continent due to several factors such as financial barriers, poor infrastructure, limited access to advanced technologies, weak institutional framework and inadequate policies. RE increase will represent a tremendous opportunity for the continent to establish a low-carbon system and thus mitigate climate change, satisfy its growing energy demand driven by its accelerated population growth, and improve its low standard of living due to the fact that Africa is home to the largest number worldwide of people living without access to stable and reliable energy supply (Baye et al., 2021).

Therefore, RE is a key element for achieving effective sustainable energy and sustainable development, and every African country, individually and collectively, should build a suitable framework to promote its deployment. African countries differ from each other in terms of their economic and political situation, natural resources, renewables potentials and regulatory and policy framework, making them have different RE development and a heterogeneous African RE scene.

Africa represents a critical focus for energy transition studies. First, the focus on Africa in the previous studies has received less attention compared to other regions, which results in a weak policy and strategies for the development of the energy system of the continent. Moreover, analysing the African energy transition allows for better design of energy policy, affecting the economic and social development of many Africans who still lack energy access, suffer poverty and inadequate infrastructure. Lastly, Africa's abundant natural resources make it play a key factor in the global transition toward RE. Its unharnessed energy resources offer great opportunities to enhance energy access across African countries, support neighbouring regions and create new commercial ties with other countries. Thus, this study tries to give a deep and comprehensive understanding of the energy landscape in Africa over time and by country in order to identify general trends. We aim to elaborate an interpretative scheme to understand different choices of RE investments based on the structural dynamics in the energy markets and on political and socio-economic variables.

The first objective of the present research is to add to the literature review on energy transition and RE development by first studying what are the energy dynamics of some African countries, which countries have similar or different trends in terms of renewable and fossil energy and what are the factors that can influence energy structure in these countries. In order to analyse our key points, we will make use of Ward's method for cluster analysis in 25 African countries over the period 2000–2020 using 5 energy variables, in addition to the other economic, social, political and environmental factors to explain RE diffusion in the continent.

To the best of our understanding, this research is the first to address these points for Africa using cluster analysis. Although previous analyses have focused on some aspects of the African energy landscape, no previous work has employed this methodology to obtain clusters of African countries based on some energy variables and discuss the identification of each group by other socio-economic, political and environmental determinants. Previous researchers in the field have only addressed the factors affecting RE development without considering different attitudes of the countries that we have tried to gather in the clusters. Accordingly, our contribution provides strategic guidance for policymakers in the energy field, that starting from each cluster of countries, they can outline strategies that are better adapted to the

specific needs and conditions of each group. Not only, these recommendations serve as valuable insights and support for socio-economic development policymakers and those seeking to accelerate progress toward broader SDGs simultaneously (Nations, 2015).

This paper is organized as follows, the next paragraph will include a brief overview of RE status in Africa. The third section will present the literature review on the determinants of RE. In the fourth section, we will introduce the data and the methodology utilized in our research. Lastly, the last two sections will discuss the results obtained and the conclusions.

2. Renewable energy development in Africa

Africa holds plenty of natural resources which makes it one of the richest continents in the world in terms of natural sources including solar, wind, hydro and bio-energies, in addition to different mineral resources required for energy production and development. Regardless of this abundance, the continent could harness only a small fraction of its total diversified potential including solar and hydro in most of the countries, wind in the coastline and geothermal in East Africa (Olanrewaju et al., 2019).

However, Africa's installed capacity is still far behind compared to other regions, representing only 1.7% of the global installed capacity.

As the installed capacity grew, renewables generation and consumption have also grown to reach 19192951 TJ and 15246458 TJ in 2020, as reported by the International Energy Agency (IEA) (IEA, 2023a). Solar and wind are the most consumed renewable sources in the continent with almost 80% of total renewable consumption. As shown in Fig. 1, the largest consumers are West African and East African regions with an average consumption of 4280048 TJ and 2580250 TJ between 2000 and 2020, respectively. Among them, Nigeria registered the highest consumption in the last years accounting for 37645170 TJ on average. In 2019, the share of RE in the total final consumption in the country represented 81.4%. In addition, the country has shown a serious commitment to renewable investments and according to IRENA, Nigeria is one of the top recipients in the world of public investments in renewables with 7639\$ million between 2011 and 2020.

However, despite not having a large consumption of renewables, countries like Congo, Somalia and Gabon are considered the greenest countries and had the highest shares of RE in their total final energy consumption in 2019 with 96.24%, 95.03% and 89.88%, respectively (IEA, 2023a).

Based on IEA statistics, although Egypt and Morocco have devoted a huge commitment to renewables, North Africa remains the lowest in terms of RE consumption, with an average of 170809 TJ from 2000 to 2020. Morocco and Egypt are the highest investors in RE after Nigeria accounting for 5322.84\$ million and 4775.66\$ million between 2009 and 2020, respectively (IRENA, 2023). As for Algeria, it is the lowest consumer of RE in the whole continent and registered 1544 TJ between 2000–2020 and its share of RE consumption was only 0.16% of the total in 2019. This is expected given that Algeria heavily relies on FF and it is a great producer and exporter of gas and oil. However, Algeria has RE potential and since 2011, the country has introduced policies to diversify its energy mix and promote the development of renewables (Zahraoui et al., 2021).

Southern countries such as South Africa, Mozambique and Zimbabwe have worked intensively in RE development. Mozambique and Zimbabwe had notable shares of RE in their final consumption of 79.5% and 81.5% in 2019, respectively. For South Africa, even though the RE share is low compared with the region, the country covers the highest installed capacity of renewable technologies in Africa as it is the most technologically advanced country in the continent (Salahuddin et al., 2019).

Overall, most of the continent has manifested a strong interest in RE, leading to a more diversified energy mix. Renewable sources have become increasingly important in recent years, driven by various factors influencing their growth.

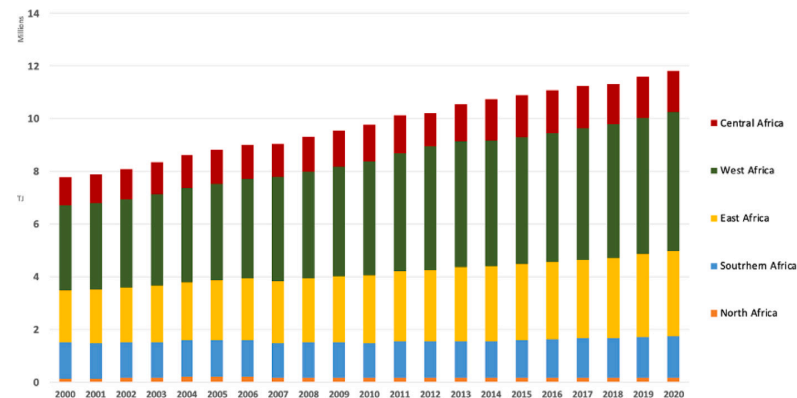


Fig. 1. Renewable energy consumption by African region (TJ) 2000–2020.

Source: Own elaboration based on IEA statistics, 2023.

3. Literature review on renewable energy determinants

The literature on RE development and related issues is wide but studies that focus on RE determinants and the factors that influence its deployment are considerably scarce due to the fact that it is a new area of research. Most of these studies were mainly concentrated on developed countries given that access to the data was much easier and those interested in developing countries are few, particularly those focusing on African countries. The available analyses on the RE determinants have highlighted different categories of drivers namely socio-economic, political, environmental, technological and country-specific factors. In this part, we try to present some of these studies and we first start with those on a global sample of countries and after on African economies.

Marques et al. (2010) have analysed the motivations that stimulate RE in 24 European countries over the period 1990–2006 applying fixed effects vector decomposition. They included in their analysis variables such as income, energy consumption, FF prices, energy imports, CO₂ emissions and other variables. Briefly, they concluded that the lobby of FF and CO₂ emissions does not encourage RE use in European countries, while the aim of gaining energy security is important to push RE development. Same for income but GDP is a RE driver, particularly in the European Union countries.

Omri and Nguyen (2014) carried out an analysis to examine the effects of economic development, oil prices, CO₂ emissions and trade openness on RE consumption using a global panel for 64 countries between 1990 and 2011 and applying a dynamic system-GMM panel model. As a next step, they considered 3 subpanels based on the income levels of the countries: high-income, middle-income and low-income. Their results suggest that the changes in carbon emissions positively impact RE energy consumption in all subpanels studied and it is the same for the trade openness excluding the high-income sample. As for GDP per capita, they noticed a significant effect only for high- and low-income panels. And finally, oil price changes have a negative but small impact on the middle-income subpanel and the global sample that includes the 64 countries. These results contradict those found by Kilinc-Ata (2016) in his study on 27 EU countries and 50 US states from 1990 to 2011. The study mainly analyses the effectiveness of four instruments of RE policy namely feed-in tariffs (FITs), tenders, tax and the most commonly used policy, quota in diffusing RE sources. Their findings showed that the first 3 categories FITs, tenders and tax incentives provided positive results on RE capacity in the countries and states studied while quota had no significant impact. Additionally, coal price, nuclear and electricity consumption are important factors to encourage RE deployment but income, security variables, gas price and CO₂ emission are not.

On the other hand, Sweidan (2021) examined in his study whether the geopolitical risk influences RE deployment in 10 net crude oil importer countries (Brazil, China, India, Indonesia, Malaysia, Philippines, South Africa, South Korea, Thailand and Turkey) from 1985 to 2017. The results of the Autoregressive Distributed Lag model (ARDL) suggest that geopolitical risk has a significant and positive impact on RE deployment and thus it is not an obstacle but an incentive to RE diffusion.

More recently, Kazemzadeh et al. (2023) investigated the relationship between the share of electricity consumption from RE, economic complexity, financial development and oil prices. First, differently than the mentioned studies, using a global sample composed of 49 countries and a club convergency analysis, they identified seven subgroups that are convergent among their group members and only one non-convergent group. As a second step of the analysis, they employed the PVAR method to test the relationship between the variables. The results show that economic complexity and oil prices have a one-way relationship. The rest of the variables have bi-directional Granger causality relationships at a 1% significance level.

Another important determinant for renewable use, which has not been well developed in the literature, is technology. The findings of Chishti and Dogan (2024) add to this gap and reveal this importance in the top 10 renewable energy-consuming countries. According to their analysis, technology i.e. information technologies (ICT) positively impact RE in 3 different channels. First, by financing green projects in RE, secondly, through its role in minimizing production costs, and thirdly, by reducing the cost of communication, computation, and data processing enabling faster and broader access to symmetric and necessary information regarding finance facilities and investment decisions.

Although there are plenty of studies on developed countries and large economies, research on the determinants of RE in Africa is relatively scarce. Ackah and Kizys (2015) for instance, conducted an analysis on RE demand determinants including GDP per capita, energy prices, energy consumption and carbon emissions in 12 oil-producing African countries for 42 years over the period 1971–2012. To do so, they made use of a one-way fixed effects model, a one-way random effects model and a dynamic panel data model. According to the results obtained, GDP per capita and energy consumption have an important positive effect on RE consumption while CO₂ emissions and energy price have an inverse impact.

Economic growth is the major determinant tested in the literature on RE consumption determinants. Alabi et al. (2017) studied this relationship in the long and short term for 3 African OPEC countries which are Algeria, Angola and Nigeria for the sample period 1971–2011, applying the Fully Modified Ordinary Least Squares model (FMOLS) for heterogeneous cointegrated panels. The findings confirmed the

existence of a bi-directional causality relationship between GDP per capita and RE consumption in the short and long run. Further, they also found a bi-directional relationship between GDP and non-renewable energy, a bidirectional nexus between GDP and carbon emissions and a unidirectional causality running from non-renewable energy consumption to CO₂ emissions. In their paper, [da Silva et al. \(2018\)](#) investigated RE drivers in 17 Sub-Saharan African countries for 25 years (1990–2014) through the application of the panel-ARDL method. The authors pointed out that economic growth and the use of energy are positively correlated to RE and encourage its implementation in the Sub-Saharan region while FF price, CO₂ emission, imports, Kyoto Protocol ratification and population growth did not contribute to its integration in the period and countries included in the studies.

Contrary to [da Silva et al. \(2018\)](#), the link between economic development (GDP per capita) and RE was found to be negative in the analysis of [Ergun et al. \(2019\)](#) including 21 African countries over the period 1990–2013. The results of random-effects Generalized Least Squares regression used in their study revealed also that Human Development Indicator (HDI) negatively impacted RE deployment, FDI in the other hand showed a positive effect but the level of democracy did not manifest a direct relationship with RE.

[Ankrah and Lin \(2020\)](#) discussed some of the previously mentioned factors in Ghana as a case study from 1980 and 2015, relying on a Vector Error Correction Model and Johansen cointegration technique. As a result, they obtained a positive relationship between FDI and RE and trade openness and RE, coinciding with the results of previous studies. GDP per capita, on the contrary, was found to be positive but insignificant and fossil development and financial development had a negative influence on renewable electricity.

For Nigeria, one of the continent's largest consumers of renewable sources, [Foye \(2023\)](#) proved that some macroeconomic factors are the drivers of renewable consumption. Including an autoregressive distribution lag technique, the author highlighted that climate change explains renewable sources implementation only in the short run and government spending on education and health has only a minimum impact. In contrast, oil returns and interest rates have a negative relationship with RE penetration.

Another work highlighting the role of climate and environmental sustainability and human capital development in assessing renewable electricity adoption is conducted by [Olanrele and Fuinhas \(2024\)](#) for a group of Sub-Saharan countries. According to the authors, FF consumption, which is the main cause of environmental impacts, together with the increment in knowledge, has led to an increase in renewable sources. Not only that, but the study has also discussed some of the main barriers to green transition, which are FDI, RE policy framework and regulatory policy.

Considering the factors mentioned, we notice that African energy strategies differ from those in other regions. For example, European countries have implemented specific policy instruments as indicated in the analyses of [Marques et al. \(2010\)](#) and [Kilinc-Ata \(2016\)](#). These instruments including feed-in tariffs and tax incentives have contributed to stable returns for investors and a reduction of market risks, facilitating RE adoption. In contrast, for Africa, the replication of such strategies is limited by different challenges such as its poor infrastructure, the financing barriers and the fragile policy frameworks. Additionally, Africa's socio-economic context, marked by low incomes, high poverty, low technological advancement and high dependence on fossil resources, requires adequate strategies. Furthermore, energy transition strategies not only vary between Africa and other regions but also among African countries, reflecting different socio-economic conditions, energy landscapes and policy environments.

Previous analyses have discussed some of these aspects and particularly focused on the factors stimulating the implementation of renewable sources in different economies, using various econometric and statistical tools, which strengthens the previous findings. Despite that, the African contest has received less attention and existing studies

have not examined the differences and similarities in energy dynamics nor discussed the socio-economic, political and environmental determinants characterizing different groups of countries and particularly their RE consumption. In the next section, we fill this gap by discussing how African countries differ in terms of RE and the factors affecting each group, using cluster analysis, a technique that, to our knowledge, has never been employed for African countries using energy variables.

4. Data and methodology

4.1. Data

4.1.1. Data collection

To analyse RE development and its determinants in Africa, our research makes use of a set of variables bought and collected from different international databases as indicated in [Table 1](#).

Since we aim firstly to understand the energy dynamics of African countries, we included a set of energy variables that cover renewable and non-renewable energy to better capture the transition from FF to renewables. To this end, we considered the production and consumption of RE, which reflect the use of renewable resources and their demand and supply dynamics. Similarly, we employed the production and consumption of FF to assess the country's reliance on traditional energy. In addition, we included FF imports to highlight countries' dependency on foreign resources to satisfy their energy needs. We also considered including FF exports to have a better understanding of the role of these countries in the global energy market, but this was not possible due to data limitations. The selected energy-related variables are those used in the cluster analysis and they are defined as follows:

- **RE production:** is the total production of various technologies of RE namely hydropower, geothermal, solar photovoltaic, solar thermal, wind energy, tide energy, different types of bioenergy such as biogases, biogasoline and biodiesel and municipal waste.
- **RE consumption:** is the total consumption of the RE types as specified for the production.
- **FF production:** is equal to the sum of the production of oil including oil shale and oil products, coal including coal and coal products and natural gas.
- **FF consumption:** is equal to the sum of oil including oil shale and oil products, coal including coal and coal products and natural gas.
- **FF imports:** are the sum of oil, coal and natural gas imports. For coal, it includes the external quantity obtained from other countries excluding coal in transit. As for oil imports, excluding the oil in transit, they comprise the amount of crude oil and oil products (under processing agreements). As reported by the World Energy Balances of the IEA, crude oil, NLG and natural gas imports are considered as received from the country of origin while refinery feedstocks and oil products are mentioned as coming from the country of last shipment. For the LNG which is imported from other countries, when it is exported to another country after the regasification process, it is considered import and export.

The other variables that are considered for discussing the factors influencing RE development in each cluster of countries are as follows:

- **GDP per capita:** the Gross Domestic Product divided by the midyear population.
- **Foreign Direct Investment:** the inflow of foreign direct investment into a country and it is equal to the sum of equity capital, reinvestment of earnings and other capital, according to the World Bank.
- **Trade openness:** the total of imports and exports of goods and services.

Table 1
Summary of the variables included in the analysis.

Variables	Description	Source
RE production	The RE production, expressed in Terajoule (TJ).	International Energy Agency (IEA) ^a
RE consumption	The RE consumption, expressed in TJ.	International Energy Agency (IEA) ^a
Fossil fuels production	Fossil fuels production expressed in TJ.	International Energy Agency (IEA) ^a
Fossil fuels consumption	Fossil fuels consumption expressed in TJ.	International Energy Agency (IEA) ^a
Fossil fuels imports	Fossil fuels imports expressed in TJ.	International Energy Agency (IEA) ^a
GDP per capita	Gross Domestic Product per capita expressed in current US\$.	World Development Indicators ^b
Foreign Direct Investment	Foreign Direct Investment expressed in current US\$.	World Development Indicators ^b
Trade openness	Imports and exports of goods and services, expressed as % of GDP.	World Development Indicators ^b
Political stability	Political stability and absence of violence/ terrorism (from −2.5 to 2.5).	World Development Indicators ^b
Level of democracy	The level of democracy index ranging from 0 to 100.	Freedom House ^c
WESII	World Economic and Social Impact Index (from 0 to 100).	World Economics ^d
CO2 emissions	Carbon dioxide emission, expressed in kiloton (kt).	World Development Indicators ^b

^a Bought from the International Energy Agency, World Energy Balances. (IEA, 2023b).

^b The World Bank Group 2023. DataBank, World Development Indicators (World Bank, 2023).

^c Freedom House website (Freedom House, 2023).

^d World Economics website (World Economics, 2023).

- **Political stability:** the political stability and absence of violence/terrorism is an assessment of the political and security level within a country's political environment. It is an index that gives a score from roughly −2.5 to 2.5 for each country, in units of a standard normal distribution as described by the World Bank.
- **Level of democracy:** measures the access to political rights, civil liberties and the level of freedom in a country considering the right to vote and freedom of expression and equality before the law.
- **World Economic and Social Impact Index:** measures the economic and social situation within a country and it covers social indicators mainly related to education (years of schooling, education spend % of GDP, health (life expectancy, median age) and employment (population in employment). It gives a score ranging from 0 (poor) to 100 (very good).
- **CO2 emissions:** the emissions resulting from the consumption of FF mainly burning oil, gas and coal, from biomass and waste materials and from industrial processes such as the manufacture of cement.

The sample used in our work was chosen based on the availability of the data and included 25 African countries¹ over the period 2000–2020. The sample is restricted to data up to the year 2020 as more recent data was not available to us. It is worth mentioning that energy-related data were legally purchased from the International Energy Agency (World Energy Balances 2023 IRENA, 2023) and we obtained the necessary license for their use in our analysis. The International Energy Agency covers only 34 African countries. From them, we selected only countries with complete data for all the variables and years, since we used a methodology that requires a distance measure and thus a balanced sample without missing data (Jaeger and Banks, 2023). Also, the selected countries cover all the African regions, including North and Sub-Saharan Africa with different stages of energy transition, which provides comprehensive insights about the energy landscapes, progress and challenges faced by different countries.

¹ The countries included are Algeria, Angola, Botswana, Cameroon, Congo, Democratic Republic of Congo, Cote d'Ivoire, Egypt, Equatorial Guinea, Eswatini, Gabon, Ghana, Kenya, Libya, Morocco, Niger, Nigeria, Senegal, South Africa, Sudan, Tanzania, Tunisia, Zambia, Zimbabwe.

4.1.2. Descriptive statistics

As shown in Table A.2, the average RE consumption of all the countries in the sample ranges from a minimum of 674.37 registered in Equatorial Guinea to a maximum of 3764517.02 in Nigeria. The same as for the RE consumption, the lowest average production is recorded in Equatorial Guinea and the highest was for Nigeria. All in all, Nigeria is the highest African producer and consumer of RE with 5058970.4 TJ and 4639446.6 TJ in 2020, respectively while Equatorial Guinea is the lowest in terms of RE production and consumption accounting respectively for 3156 TJ and 145 TJ in 2020.

For FF, the maximum consumption was highlighted in South Africa with an average of 1680958.2 TJ and the minimum was registered in Eswatini accounting for 1834.92152 TJ. FF production ranges between 687.77 TJ registered in Senegal and 5935617.6 TJ recorded in South Africa. The highest average imports of fossil energy were seen in South Africa and the lowest in Mozambique.

Table A.3 summarizes the variables that will be used to interpret the energy dynamics for the various countries. The average GDP per capita between 2000 and 2020 varies from a minimum of 356.08\$ recorded in the Democratic Republic of Congo to a maximum of 10403.65\$ in Equatorial Guinea. The most politically stable country is Botswana with an average index of 1.03 while the least stable is Sudan representing −2.14. The level of democracy in the continent is low with Ghana having the highest level of democracy score that is 80, and Egypt representing the least democratic country among the African countries studied in the analysis with a score of 5. The CO2 emissions in Africa are very low compared to developed countries with South Africa being the biggest emitter of CO2 with an average of 398484.34 kt and Eswatini being the least accounting for 1017.37 kt. As for FDI, the maximum average inflows are equivalent to 5239719047.62\$ and received by Egypt and the minimum inflows account for −426503104.16 in Angola. In terms of socio-economic situation, Algeria registers the highest World Economic and Social Impact Index equivalent to 73.9 and Mozambique represents the lowest score, 16.3. Finally, HDI ranges from an average of 0.72 in Libya and 0.34 in Niger.

Before conducting the cluster analysis, we studied the correlation among the variables inserted in Table A.3 and the results of the correlation matrix are presented in Table A.4.

The findings point out that:

- High FDI inflows are correlated with a high level of CO2 emissions.

- An advanced level of democracy results in a high level of political stability.
- High political stability increases trade openness and the GDP per capita.
- An elevated GDP per capita is accompanied by a better economic, and social situation and trade openness.

4.2. Methodology

In order to understand the behaviours of the African countries and to identify the possible similarities between them, we implement the cluster analysis method. Cluster analysis is a set of multivariate techniques that aims to assemble objects and individuals into groups based on their similarities. It means that the elements belonging to the same cluster are similar to each other and have a high degree of association between them while those belonging to different clusters are dissimilar and have a low association, based on the variables included in the analysis (Włodarczyk et al., 2021). The traditional estimation methods, such as regression and other econometric models, mainly study the relationships between variables. Unlike them, cluster analysis identifies groups of countries based on selected variables, which aligns with our research goals.

The clustering technique includes different methods such as k-means clustering, partitioning around medoids (PAM), Fuzzy C-means, K-medoids and hierarchical algorithms (Janse van Vuuren and Vermeulen, 2019). In the present research, we are going to make use of Ward's method applied by Kacperska et al. (2021) and Włodarczyk et al. (2021). Ward's method is the most preferred in our analysis. According to Jaeger and Banks (2023), it is one of the most commonly used cluster methods alongside K-means. However, comparing other methods, particularly, the K-means, Ward's is the most suitable to our dataset, since it is more suitable for smaller sample sizes. In addition, it minimizes the variance within the clusters, ensuring that they are as homogeneous as possible, providing more robust results. Also, the selected method does not require specifying the number of clusters in advance, instead, the optimal number can be determined by the dendrogram that it provides (Jaeger and Banks, 2023). It is worth mentioning that the clustering algorithm is preceded by a similarity or dissimilarity measure and thus before conducting the cluster analysis it is necessary to consider a distance measure. The similarity measure consists of determining the relationship between the elements and the similarity between them (Maji et al., 2019). In our case, we will adopt the Euclidean distance measure as used by Kacperska et al. (2021) and Włodarczyk et al. (2021), and it is the most commonly employed and appropriated with the ward's method. Moreover, it is known that the Euclidean distance assumes a balanced sample. We have carefully addressed this assumption and have selected only 25 African countries without missing data, as mentioned before. This limitation of cluster analysis prevented us from including more countries to better cover different regions and countries across the continent. Furthermore, before calculating the distance, a normalization was needed to ensure the accuracy and consistency of the clustering process (Jaeger and Banks, 2023).

As a first step in our analysis, in order to have a similar scale, we standardized all 5 variables namely RE consumption, RE production, FF consumption, FF production and FF imports across all countries using the z-score method defined as follows:

$$Z_{ctv} = \frac{x_{ctv} - \bar{x}_{cv}}{\sigma_{x_{cv}}} \quad (1)$$

where v denotes the variable, c is the country, t refers to the year of the observation, Z_{ctv} is the value of variable v for country c at year t , $\bar{x}_{cv}$ refers to the mean of variable v for country c and $\sigma_{x_{cv}}$ is the standard deviation of variable v for country c as indicated in Table A.2.

In the next step, we have determined the similarity between countries calculating the sum of the Euclidean distances d among the obtained z-scores and it is described as follows:

$$d_{ij}^2 = \sum_v \sum_t (Z_{itv} - Z_{jtv})^2 \quad (2)$$

where i and j refer to two countries within the dataset.

After calculating the distance between the countries included in the dataset, we carried out a cluster analysis applying Ward's aggregation methodology. Through Ward's, we have classified the countries into clusters that are different to each other. In the last step, we conducted an analysis using the values included in Table A.3 to characterize the different groups.

5. Results and discussion

5.1. Clustering results

After data normalization and Euclidean distance measure among the scores resulting from the normalization, we ran the cluster analysis using Ward's method as previously described. We obtained a dendrogram as shown in Fig. 2 including different possible clusters. The optimal number of clusters was figured out based on optimizing data fitting by minimizing dissimilarities within clusters and maximizing dissimilarities between clusters to offer the most pertinent clusters. We identified four representative clusters: cluster A, cluster B, cluster C and cluster D (for a summary of the clusters see Fig. 3).

Observing the distribution of values in various groups, we affirm that the first cluster A groups a number of 6 countries namely Gabon, Dem Rep of Congo, Zimbabwe, Libya, Eritrea and Eswatini. It is characterized as the lowest importer and the most exporter of FF and we label them as "Brown dependent countries", as they are dependent on energy imports of other countries. Countries like Libya and Gabon belong to this cluster because they are great exporters of FF and their economies depend heavily on energy exports. Accordingly, they have significant energy auto-sufficiency, contributing to their energy security.

Cluster B reunites 6 countries: Niger, Zambia, Congo, Mozambique, Ghana and Cameroon and it is found to be the least producer and consumer of energy. Countries of cluster B are identified as "Grey countries", since they are the least contributor to CO2 emissions resulting from fossil production and consumption, compared to other countries. Niger and Zambia represent a good example, as they are one of nations with limited access to energy resources.

Cluster C brings together 9 countries that are Côte d'Ivoire, Sudan, Nigeria, Tanzania, Tunisia, Senegal, Egypt, Equatorial Guinea and Angola. In this cluster, we can observe countries with the most use of RE which means the highest production and consumption of RE, they can be considered "Green countries". Nigeria, alongside Tanzania and Sudan is among the largest producers and consumers of RE in Africa, playing a crucial role in driving the continent's green transition.

Lastly, cluster D includes 4 countries namely South Africa, Botswana, Morocco and Algeria. Unlike cluster C, these countries have the highest production and consumption of FF. So, they represent the "Brown countries" of Africa. South Africa, Algeria and Botswana are large economies with a significant reliance on fossil energy. Algeria, in particular, is known for its abundance of energy resources, making it one of the greatest gas exporters worldwide.

As a last step of our work, we tried to discuss the other socio-economic, political and environmental factors that explain each cluster using the variables included in Table A.3.

The results are presented in Table A.5. Fig. 4 presents the radar plot of the 4 clusters using the means of each variable included in Table A.5 for each cluster. We have constrained the values between -1 as a minimum and 1 as a maximum.

As shown, cluster A has the highest average of trade openness accounting for 80% of GDP and this could be explained by the fact that

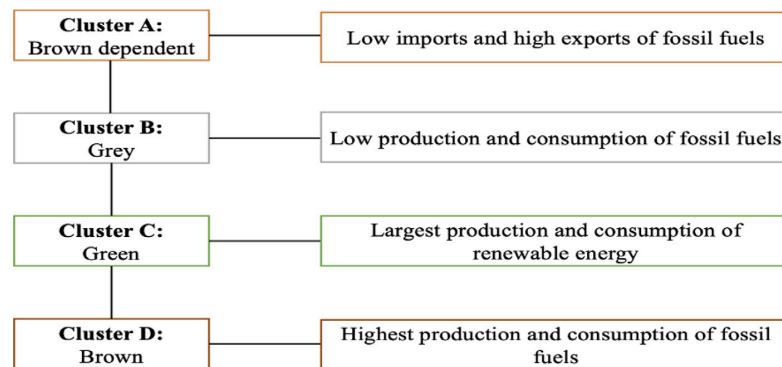


Fig. 2. Cluster analysis results applying Ward's method.
Source: Authors elaboration.

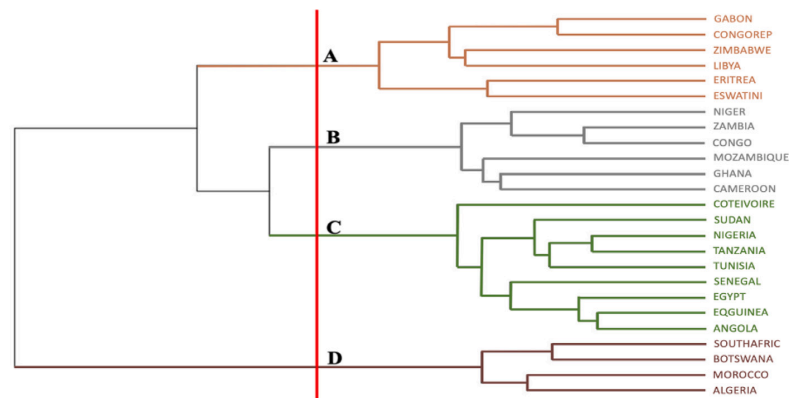


Fig. 3. Summary of the clusters and their characteristics.
Source: Authors elaboration.

it takes advantage of energy commercial flows. Yet, the countries of this cluster are those who suffer the most from fragile political stability and low level of democracy and Libya is a good example of this.

On the other hand, cluster B characterized by low production and consumption of FF includes the least economically developed countries in the sample which have the lowest average GDP per capita compared to the other clusters and also have the lowest social conditions with an average World Economic and Social Impact index of 34.97.

Cluster C encompasses countries with high political instability but at the same time, they receive massive foreign investments, which demonstrates that an economy that is mainly based on RE may represent a great opportunity for investments and can be a lever for green economic development.

The last cluster D shows that major FF production in these countries is likely to lead to internal economic and social development as they represent the highest average GDP per capita and the highest average World Economic and Social Impact index. However, cluster D has the highest CO₂ emissions confirming that high levels of FF production give rise to high degrees of CO₂ emissions.

Comparing the obtained clusters, we notice similar and different trends in their energy dynamics but also regarding the development factors. Clusters A and D share a strong dependency on FF. Cluster A is an important exporter of fuels, resulting in sufficient domestic energy production, same as Cluster D. Both clusters directly contribute to CO₂ emissions, resulting in high ecological costs. However, they are found to have a good economic situation. Like Clusters A and D, Cluster C shows high production and consumption of energy, but with more

reliance on renewable resources, which contributes to reducing CO₂ emissions. Similar to Cluster C, cluster B, leads to fewer emissions due to its lower energy consumption. Consequently, these countries face significant economic challenges, which highlights the trade-off between economic and environmental sustainability.

5.2. Cluster framework and policy implications for SDGs alignment

The findings of our analysis provided better insights into the energy dynamics of African countries, allowing us to identify both similarities and differences among them, thus addressing the first objective of our study. The identified clusters revealed interactions between these countries in terms of energy and also in terms of socio-economic and environmental sustainability, responding to the second objective of the work. Moreover, the analysis of the contributing factors for each cluster aligns with SDGs (Nations, 2015).

The United Nations SDGs stand as a global mandate to eradicate poverty, safeguard the environment, and ensure universal prosperity by 2030 (Nations, 2015). These goals offer a comprehensive blueprint for tackling urgent global issues while nurturing sustainable progress across economic, social, and environmental spheres. Serving as a guiding framework, the SDGs rally governments, organizations, and communities worldwide toward a future marked by fairness, inclusivity, and sustainability. By addressing interconnected challenges like poverty, inequality, climate change, and environmental degradation, the SDGs endorse holistic development approaches that acknowledge the intricate relationships between diverse sectors and stakeholders.

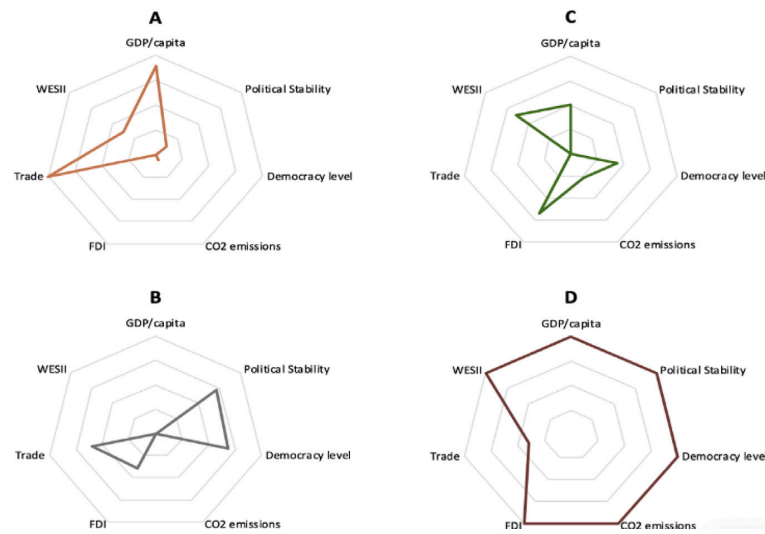


Fig. 4. Radar plot for the 4 clusters.
Source: Authors elaboration.

Within Cluster A, characterized by extensive trade openness and reliance on energy commerce, the focus lies on harnessing RE sources to propel economic growth while concurrently tackling political instability and fortifying democratic institutions. This endeavour resonates with SDG 7 (Affordable and Clean Energy) by championing sustainable energy practices and SDG 16 (Peace, Justice, and Strong Institutions) by fostering stability and effective governance. Implementing policies to foster RE adoption and sustainable infrastructure investment is vital, alongside efforts to fortify democratic structures and prioritize investments in education, healthcare, and social welfare to promote inclusive development and alleviate poverty.

Cluster B, marked by low FF production and consumption yet grappling with economic underdevelopment and social hurdles, necessitates targeted interventions to foster inclusive growth and diminish disparities. This corresponds with SDG 10 (Reduced Inequalities), underlining the significance of addressing income disparities and providing equal opportunities. Equally critical is enhancing access to essential services like healthcare and sanitation to elevate living standards and well-being. Diverse actions have been taken in this regard such as the Energy For All (ProEnergia) project in Mozambique. The project aims to provide access to electricity services in the country, specifically, in rural areas and the poorest provinces to reduce inequalities in the country (SDG 10) (World Bank, 2019).

In Cluster C, characterized by political volatility alongside notable foreign investments, strategies must leverage RE as a catalyst for sustainable economic advancement while concurrently addressing governance shortcomings. This is in line with SDG 9 (Industry, Innovation, and Infrastructure) by fostering innovation and infrastructure development and SDG 16 by promoting stable and inclusive governance. Establishing partnerships among governments, private sector entities, and civil society to attract sustainable investments in RE, strengthening regulatory frameworks, and supporting peacebuilding are imperative to mitigate political instability and foster sustainable development. The African Development Bank's Desert to Power Initiative stands as a good example of the dynamics of this cluster. Despite political volatility and high vulnerability, countries of this cluster (Nigeria, Senegal and Sudan) among others have received important investments in order to address access to energy issues and provide affordable and clean energy (SDG 7) (African Development Bank, 2024). Such an ambitious project shows how RE development could be possible even in the presence of political instability.

Lastly, Cluster D, emphasizing FF production and high CO2 emissions, necessitates a shift toward cleaner energy sources to combat environmental degradation while safeguarding economic prosperity. This corresponds with SDG 7 and SDG 13 (Climate Action), advocating for clean energy solutions and climate change mitigation. Implementing policies to promote energy efficiency, introducing carbon pricing mechanisms, and investing in research and innovation to expedite the deployment of RE solutions are vital within Cluster D to ensure a sustainable transition toward clean and RE sources.

It is worth mentioning that some of our findings are in line with previous studies on energy transition and some are in contrast. For example, within Cluster A, we found that despite political instability, this cluster has high trade openness which is consistent with previous economic research on this relationship (Asongu et al., 2021). However, in cluster C, we observe massive FDI inflows despite political instability, contradicting most of the existing studies (Rashid et al., 2017; Khudari et al., 2021). In our analysis, this relationship can be explained by additional factors that contribute to their green transition such as their abundance of natural resources. These aspects deserve deeper discussion and analysis in further research, especially from economic and political perspectives.

Additionally, while African countries have great potential for RE development, taking advantage of this potential is challenging, as identified in the different clusters. In addition to the weak governance, regulatory framework and political instability, the lack of infrastructure and financial barriers also play a crucial role in Africa's energy and sustainable transition. Certain areas, especially rural regions, still lack access to electricity as they are still disconnected from national grids. Furthermore, RE projects require larger initial investments than conventional energy projects, making it difficult to cover costs with the existing limited resources.

6. Conclusion and policy implications

In the present research, we discussed RE development in the African continent during the last twenty years. We first presented the current situation of RE and how it is dispersed between countries, in addition to the factors that influence its deployment.

To answer our first research objective of understanding the energy dynamics among African countries and identifying similar and different

groups, we performed a cluster analysis using Ward's method on a sample of 25 African countries over the period 2000–2020. To do so, we made use of energy variables which are RE consumption, RE production, FF consumption, FF production and FF imports. The results of the cluster analysis suggest four groups of countries based on their energy dynamics. Cluster A has countries with the lowest imports and highest exports of FF. In cluster B there are the least producers and consumers of FF. Cluster C includes the most producers and consumers of RE and countries in Cluster D are the most producers and consumers of FF.

The composition of each cluster is also explained by other variables that we employ in the analysis mainly socio-economic, political and environmental, which we employed to address the second research objective of identifying the factors influencing the dynamics in each cluster. Based on the findings of the last analysis, we assume that, for the countries that belong to cluster A, the production of FF energy is boosted by foreign markets, so the transition can be arduous and linked to the relationships with the other countries. However, RE could represent an opportunity for attracting foreign investments as long as policies that aim at improving the levels of democracy in the various countries are implemented. The investments in renewables could be a driver for the economic and social development of countries comprised also in cluster B. In this cluster, the transition process could be easier because, due to the low production and consumption of fossils, the production of RE can grow faster. In cluster C, the investments in renewable sources are correlated with an advanced level of Foreign Direct Investment. For these countries, it is expected green economic growth that could lead to better social conditions in the future, growing levels of democracy and greater political stability. The countries of cluster D should initiate RE incentive policies as soon as possible in order to gradually substitute FF production and thus reduce the high CO₂ emissions. In this cluster, since the countries have developed economies and as a consequence, an important production and consumption of FF, the process of energy transition toward renewables may take more time and effort because it requires structural changes. For these countries, we can suppose that there will be necessary changes in the supply and demand of energy resources, technological innovations and a new industrial policy.

Additionally, each cluster, from A to D, requires tailored strategies aligned with specific SDGs. For instance, Cluster A needs policies promoting RE adoption and democratic stability (SDG 7 and SDG 16). Cluster B requires targeted interventions to promote economic diversification and reduce inequalities (SDG 10). Cluster C demands strategies leveraging RE and enhancing governance (SDG 9 and SDG 16). Finally, Cluster D necessitates transitioning to cleaner energy sources to combat

climate change (SDG 7 and SDG 13). These specific recommendations represent a roadmap for energy transition in the indicated groups, particularly, countries having similar conditions. They aim to enhance the energy transition of the African countries, which based on the current energy system, still have a lot to implement to achieve a sustainable and secure energy system. Furthermore, specific recommendations can help these clusters accelerate their sustainable development, which in turn may influence SDGs since Africa is a key factor in the achieving of the global agenda.

Finally, we suggest that further deep analysis of energy dynamics in these countries is needed in addition to country profile analysis for a better definition of policies to achieve a higher green economic development. Still, due to certain limitations related to up-to-date data availability and methodological assumptions, we could not rely on more countries. Also, in our work, we employed cluster analysis based on specific variables and Euclidean distance metric, which represents another limitation. Future researchers may focus on comparing different results from different sets of variables or clusterisation procedures to ensure the robustness of the findings.

CRedit authorship contribution statement

Emna Kanzari: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Gioacchino Fazio:** Visualization, Project administration, Investigation, Conceptualization. **Stefano Fricano:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

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

Data availability

The authors do not have permission to share data.

Appendix

Table A.2
The means of each energy variable for each country 2000–2020.

Country	RE cons.	RE prod.	FF cons.	FF prod.	FF imports
Algeria	1543.98 ^a (1070.72) ^b	2874.59 (923.46)	1048483.45 (340290.84)	3118264.61 (243909.11)	100505.95 (62690.58)
Angola	179663.84 (17056.79)	252745.48 (33464.39)	152249.65 (54654.73)	3108107.74 (822070.41)	117214.02 (71296.63)
Botswana	20666.24 (1860.97)	21787.72 (830.80)	39724.18 (4587.23)	31582.71 (13374.87)	36275.61 (5915.81)
Cameroon	210878.89 (24159.64)	248794.93 (38115.65)	50027.58 (10270.27)	196932.71 (32551.94)	80744.66 (13481.15)
Congo	34681.63 (16916)	48032.44 (19867.89)	19041.28 (7424.49)	593269.59 (84965)	7636.1 (5201.18)
D. R. of Congo	711924.78 (96132.52)	907407.44 (256352.12)	26327.27 (13083.61)	49667.17 (3767.65)	31711.26 (14320.89)
Cote d'Ivoire	169954.93 (33795.31)	273501.04 (47329.18)	65506.85 (20973.99)	128242.65 (31191.16)	147416.52 (16261.88)
Egypt	674.37 (2913.45)	1834.92 (16794)	42526.09 (279787.51)	708790 (477243.35)	9725.88 (377288.14)
Equ. Guinea	62229.69 (39.05)	188519.4 (840.62)	1568700.76 (18010.51)	3066723.57 (205584.74)	578800.56 (2223.74)
Eswatini	22378.19	28010.73	4236.23	7808.1	8345.57

(continued on next page)

Table A.2 (continued).

Country	RE cons.	RE prod.	FF cons.	FF prod.	FF imports
	(2503.97)	(3938.7)	(881.53)	(3798.87)	(1283.01)
Gabon	122 028.7 (43457.98)	125 529.02 (43562.76)	20 496.76 (8273.76)	516 063.72 (42564.64)	12 492.93 (6755.24)
Ghana	112 656.41 (10687.01)	170 919.72 (17867.61)	112 028.96 (38502.81)	146 523.62 (164675.65)	167 564.48 (47773.05)
Libya	9746.17 (1126.32)	21998.18 (4063.66)	352 203.64 (44613.03)	3083832.85 (1114984.91)	−6636.08 (123050.62)
Morocco	59 582.51 (13391.83)	73 298.91 (12284.05)	394 510.72 (88334.47)	2691.52 (585.40)	683 796.66 (134975.71)
Mozambique	217 249.55 (37549.07)	336 844.55 (28350.17)	43 520.42 (19387.54)	207 765.99 (183023.07)	−48844.26 (39256.78)
Niger	73 465.08 (19719.84)	75 596.51 (19744.92)	13 624.67 (5977.70)	17 810 (18099.81)	8288.97 (3647.48)
Nigeria	3764517.02 (605918.72)	4068834.51 (700438.15)	723 081.04 (209978.91)	5861826.69 (488768.58)	551 739.41 (267455.35)
Senegal	39 913.61 (9712.69)	66 081.54 (14518.70)	47 019.71 (10474.72)	687.77 (446.58)	103 006.11 (27969.57)
South Africa	224 544.09 (40667.51)	343 001.57 (54084.19)	1680958.2 (193514.91)	5935617.6 (266276.73)	1188898.94 (213264.15)
Sudan	276 239.9 (15413.94)	495 014.26 (27077.03)	150 710.13 (49998.68)	519 008.63 (317511.45)	52 920.71 (32105.54)
Tanzania	597 972.3 (71822.73)	683 319.59 (86438.91)	73 458.04 (29256.33)	161 491.39 (26536.44)	77 875.82 (27167.84)
Tunisia	37 707.3 (2902.59)	47 914 (3730.79)	212 083.41 (25987.55)	230 796.48 (39628.99)	270 000.74 (48828.82)
Zambia	204 597.25 (26027.76)	307 959.05 (41242.28)	39 117.14 (14524.53)	7271.97 (9266.08)	41 651.05 (15196.98)
Zimbabwe	273 033.2 (27711.10)	293 529.48 (28007.46)	62 159.01 (10226.72)	87 881.06 (27484.45)	42 963.24 (12724.89)

^a Each value refers to the mean of each variable for each country.^b Values in () refer to the standard deviation of each variable for each country.

Table A.3

The means/ last available values of each variable for each country between 2000–2020.

Country	GDP/ capita ^a	Pol. Stab. ^a	Dem. level ^b	CO ₂ ^a	FDI ^a	Trade ^a	WESI ^b
Algeria	3808.73	−1.19	32	121 781.5	1.42E+9	63.21	73.9
Angola	2637.04	−0.63	28	21 571.34	−0.42E+9	94.23	30.6
Botswana	5512.55	1.03	72	5052.18	0.28E+9	95.4	58.8
Cameroon	1300.38	−0.75	15	7033.89	0.47E+9	46.04	41.4
Congo	2235.13	−0.72	17	4953.2	1.11E+9	123.68	39
D. R. of Congo	356.08	−2.12	19	2655.77	108E+9	61.22	21.1
Cote d'Ivoire	1656.63	−1.41	49	7648.7	0.44E+9	56.53	44.2
Egypt	2233.9	−0.99	5	189 485.25	5.24E+9	46.66	70.4
Equ. Guinea	10 403.65	−0.03	18	5050.73	0.68E+9	112.71	70.4
Eswatini	3214.78	−0.22	17	1017.37	0.05E+9	111.37	35.3
Gabon	7132.09	0.19	20	5723.2	0.68E+9	82.77	65.7
Ghana	1280.27	0.01	80	10 892.84	2.01E+9	79.4	56.7
Libya	9236.53	−0.9	10	51 476.51	0.85E+9	79.3	68.2
Morocco	2789.06	−0.39	37	51 661.09	2.22E+9	67.23	65.2
Mozambique	483.71	−0.13	45	3742.02	2.08E+9	82.15	16.3
Niger	424.57	−0.85	51	1378.77	0.39E+9	40.02	25
Nigeria	1883.2	−1.91	43	99 958.39	4.16E+9	36.51	31.1
Senegal	1186.06	−0.19	68	7358.39	0.42E+9	56.50	70.50
South Africa	6052.51	−0.12	79	398 484.34	4.22E+9	53.27	65.1
Sudan	1374.78	−2.14	10	14 850.33	1.35E+9	26.07	65.4
Tanzania	725.94	−0.37	36	7993.44	0.99E+9	39	38.1
Tunisia	3529.07	−0.34	56	26 822.05	1.09E+9	94.25	69.6
Zambia	1133.3	0.23	54	3795.44	0.85E+9	69.18	31.4
Zimbabwe	965.75	−0.99	28	10 634.53	0.20E+9	69.03	41.9
Total	71 555.7	−14.94	889	1061021.26	31.87E+9	1685.73	1195.3

^a Indicates the mean calculated from 2000 to 2020.^b Refers to the last available year.

Table A.4
Correlation matrix.

Variables	GDP/ capita	Pol. Stab.	Dem. level	CO2 emis.	FDI	Trade	WESII
GDP/capita	1						
Political Stability	0.348	1					
Democracy level	−0.145	0.468	1				
CO2 emissions	0.234	−0.044	0.208	1			
FDI	−0.022	−0.196	0.084	0.742	1		
Trade	0.449	0.521	−0.057	−0.274	−0.376	1	
WESII	0.587	0.186	0.027	0.343	0.201	0.031	1

Table A.5
Means of each socio-economic and political variable by cluster.

Cluster	GDP/ capita	Pol. Stab.	Dem. level	CO2 emis.	FDI	Trade	WESII
A	4181.04	−0.80	18.8	14 301.48	0.57E+9	80.74	46.44
B	1142.89	−0.37	43.67	5299.36	1.15E+9	73.41	34.97
C	2847.80	−0.89	34.78	42 304.29	1.55E+9	62.49	54.48
D	4540.71	−0.17	55	144 244.78	2.04E+9	69.78	65.75

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Analysing the Energy Stocks Dynamics in European Countries Under an Energy Transition Framework

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Abstract

In recent years, threats to economic development due to escalating tensions related to fossil fuel use in the global energy landscape, have accelerated the need to stimulate the energy transition towards the use of renewable energy. Consequently, renewable energy, which today is seen as an important opportunity and the primary solution, has become the focus of international and local policymakers, mainly, in the developed countries that depend on fossil fuel imports such as European countries. The objective of this paper is to examine the dynamics of renewable energy in European nations by analysing the energy stock changes as a function of a set of variables mainly the production and the consumption of renewable energy. To do this, we used a Probit model considering the energy characteristics of countries as a function of their potential economic impact. The findings suggest that the increase of renewable energy proportion in the total energy supply results in a reduction in the energy stock levels in the countries studied, while greater openness to international energy markets results in an increase in energy stocks to deal with market shocks. Stretching further the analysis, the estimated parameters obtained from the Probit estimation were employed to divide the countries used in the sample into three groups based on their propensity towards a decrease in their energy stocks.

1. Introduction

In the context of energy production and consumption, the association between energy risk and fossil fuels is undeniable (Khan *et al.*, 2023). Fossil fuels, including coal, oil, and natural gas, have long been the primary sources powering the global economy (Wu, Chen, 2017). However, their dominance comes with inherent risks that span environmental, economic, and geopolitical dimensions. Firstly, the environmental risks associated with fossil fuels are manifold. Burning these fuels releases greenhouse gases, primarily carbon dioxide, into

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the atmosphere, intensifying the greenhouse effect and contributing to global climate change (IPCC, 2023).

Geopolitically, regions rich in fossil fuel reserves often experience significant geopolitical tensions and conflicts. The scramble for control over these resources has historically led to power struggles, interventions, and wars, underscoring the geopolitical risks intertwined with fossil fuel dependence.

Economically, the volatility in fossil fuel prices can destabilize national and global economies. Dependence on these exhaustible resources creates vulnerability to supply disruptions, geopolitical tensions, and market fluctuations. Furthermore, the transition away from fossil fuels towards renewable energy sources represents both an economic challenge and opportunity, with nations and industries seeking to balance energy security, affordability, and sustainability. Unlike fossil fuels, renewable energy is characterised by its abundance and not being concentrated in a specific geographic area, providing more energy independence for countries (Khan *et al.*, 2023). Many countries around the world, specifically, European countries, consume fossil energy more than they produce, which makes them heavily rely on foreign sources to meet their needs and be closely linked to the fossil exporting countries. This strong reliance can be used in some cases as a means by exporting countries to exert pressure, particularly in times of political conflicts and crises, and the tensions between Russia and the European countries are a clear and recent example of this. This crisis has highlighted Europe's over-dependence on fossil sources imports from Russia and has brought to the fore the necessity to reduce them, accelerate energy transition programs and policies, and increase the share of renewables in the energy mix, in order to obtain a more robust energy system and gain energy security (European Commission, 2022).

While fossil fuels have played a pivotal role in powering human progress, their associated risks underscore the urgent need for diversifying the global energy mix and accelerating the transition towards cleaner, renewable alternatives.

However, while renewable energies promise a sustainable future, doubts persist about their ability to fully mitigate energy risks for nations. The intermittent nature of sources like wind and solar can pose challenges to consistent energy supply, potentially leaving gaps in demand coverage. Additionally, the infrastructural demands and initial investment costs associated with renewables can be substantial, especially for developing nations. Concerns also arise regarding the scalability and storage capabilities of renewable technologies to meet growing energy demands. Hence, while renewables offer promising solutions, questions about their comprehensive role in offsetting energy vulnerabilities remain (Cergibozan, 2022).

This contribution tries to understand, through the study of the energy trends of European countries, the attitude of the various countries and whether there has been a positive effect of renewable energy on the mitigation of energy risk.

For this purpose, an analysis was developed of the trend of energy stocks in various countries over the last two decades and, which to our knowledge has never been reported in the literature, the possible interconnections with the development of renewable energy have been highlighted.

The dynamics between energy stock levels and perceived energy risk offer intriguing insights into global energy security and market sentiments. When energy stocks are abundant and surpass demand, it typically signifies a more stable energy landscape. Countries with high energy reserves, such as oil-rich nations or those with extensive renewable energy capacities, often experience reduced perceived energy risks. As the global energy landscape evolves, understanding this interplay becomes paramount for policymakers and industry stakeholders to ensure both energy resilience and public confidence.

The structure of this paper is as follows. The next section will discuss the literature review on renewable energy and energy security. In the third section, we will introduce the data and the methodology employed in the empirical work. Subsequently, we present the results and the discussion and finally, the last section summarizes and concludes.

2. Literature Review on Renewable Energy and Energy Security

Energy security is a multifaceted concept that includes different dimensions. In general, the concept refers to the ability of the country to obtain energy sources uninterruptedly and affordably to satisfy its needs. Energy security contains four main dimensions namely the availability, accessibility, affordability and acceptability (Gökgöz, Güvercin, 2018). The availability of energy resources refers to the physical existence of energy, its accessibility means the ability to reach and use energy resources despite geographical and technological constraints. As for affordability, it implies access to energy at affordable and reasonable prices. Acceptability, on the other hand, is related to the use of energy with low environmental impacts (Gökgöz, Güvercin, 2018). As commonly understood and based on several studies, fossil fuel energy is highly associated with energy security risk. Firstly, because fossil fuels are finite and will be completely consumed in the long run (Holechek, *et al.*, 2022). Secondly, they are not equitably distributed across countries and regions, which makes some countries heavily rely on imports from the other countries to satisfy their energy needs (Murshed, *et al.*, 2020). Thirdly, over the last decades, oil, gas and natural gas prices have shown significant instability (Scholten, *et al.*, 2020). Fourthly, the use of fossil fuels is strongly associated with carbon emissions and negative environmental impacts (Maji, *et al.*, 2019). That said, according to previous research, renewable energy is considered an alternative to fossil fuels in different ways and can positively

affect energy security (Cergibozan, 2022). Renewable energy (RE) contributes to the reduction of CO₂ emissions, and it has less negative environmental impacts, making it more acceptable than fossil fuels (Bilgili, *et al.*, 2016).

Additionally, despite its land and technical constraints, RE remains a better alternative to fossil fuels in terms of long-term sustainability and geographical availability, since it is characterised by its abundance all over the globe (Moriarty, Honnery, 2016). Also, renewable energy includes solar power, wind power, hydropower, geothermal energy and bio-energies. The diffusion of each of these powers generates more capacities from various sources and adds to the total energy supply of the country. According to Aslani *et al.* (Aslani, *et al.*, 2012), the higher the diversification of the energy resources in a country, the higher the diversification of the energy supply and the higher the energy security of supply. The diversification of the energy system including resources with low environmental impact and available in abundance such as renewable alternatives can allow energy security as it offers new capacities with various sources, unlike the single-energy system especially that with high environmental and security supply risk such as fossil fuels, which represent a real obstacle to sustainable development and energy security achievement (Akrofi, 2021).

The diversity in the energy resources will allow countries to have more than fossil fuels in their energy mix and may be beneficial, especially for countries that do not have high fossil production and import it from foreign markets. Energy poor countries depend on external energy countries to satisfy their increasing energy demand. By doing so, they are more exposed to market risks and dependence on other countries. By employing more renewables produced domestically, energy importing countries may reduce their reliance on external suppliers and decrease their high budget expenditure (Aslantürk, Kiprizli, 2020).

It is clear that for fossil fuel importing countries, renewable energy will guarantee a secure supply from domestic production. However, when these countries decrease their imports, it can represent a challenge for the economy and budget revenues of exporting countries which heavily depend on the revenues of energy exports. For these countries, it is important to maintain their energy exports and ensure their energy security of demand (Novikau, 2022). The Organisation of the Petroleum Exporting Countries (OPEC), are the first to be affected by the reduction of their exports as they control the oil market and between 2011 and 2019, they have seen a significant decrease in their oil exports. For OPEC, ensuring the energy security of demand is as important as the security of supply (Fan *et al.*, 2023).

Another aspect of energy security is the geopolitical conflicts between different countries to control the energy market. The use of fossil fuels is historically related to geopolitical tensions, wars and conflicts. Unlike fossil fuels, renewable

energy is expected to reduce these tensions between countries as renewable resources such as solar, wind, hydro, ocean and geothermal are equally distributed across regions. The fact that renewable resources are available for every country will offer self-sufficiency to many countries, which will decrease the energy conflicts between them (Agaton, 2022).

As previously mentioned, renewable energy plays a significant role in ensuring energy security. Despite that, the relationship between energy security and renewable energy has not been sufficiently studied empirically in the literature.

Numerous studies examined composite energy security indicators and frameworks from various angles, including inconsistencies, measurement challenges, and methodological limitations. (Siksnielyte-Butkiene, *et al.*, 2024) examined 40 different composite indicators that have been developed and used in recent years. The results indicate that many energy security indicator sets are insufficient in capturing the entirety of changes in the energy market, economy, policy, international trade, and other external factors. Despite this, many authors have reported some general considerations about some results that can be stylized. For example, analysing how renewable energy affects energy security in Lithuania, (Augutis, *et al.*, 2014) employed a scenario analysis and concluded that the development of renewable energy technologies increases energy security in the country. This effect is stronger when the share of renewables in energy production does not exceed 60-70%. (Brahim, 2014) studied this relationship in the Philippines and reached the same conclusions. The Philippines has huge untapped renewable energy and by harnessing it, it is expected to offer the country more energy security and sustainability. (Lucas, *et al.*, 2016) tested this nexus for 21 European Union countries from 1990 to 2013, making use of a set of indicators to proxy energy security: security of supply, sustainability and competitiveness. The results show the existence of a long-term relationship between renewable energy deployment and energy security. Based on the Long-range energy alternative planning (LEAP) system, (Aized, *et al.*, 2018) identified four scenarios to discuss energy plans in Pakistan. The results suggest that the green scenario which includes renewable energy sources is the best choice that the country can adopt to have low environmental and externality costs. According to (Wang, *et al.*, 2018), renewable energy can help China to enhance its energy security and reduce CO₂ emissions since the country is the world's largest oil importer and the largest CO₂ emitter. (Viviescas, *et al.*, 2019) showed that solar PV, wind and hydropower can ensure energy security in Latin America through the complementarity of these resources and regional integration. Brazil, in particular, can be a key player in renewable energy integration as it has the strongest capacity of complementarity with other Latin American countries. In the context of Eastern Europe, Caucasus and Central Asia (EECCA) countries, (Trifonov,

et al., 2021) made conclusions about the contribution of renewable energy to energy security through energy resource diversification. An increase in the share of renewable sources in the energy mix, the development of different renewable technologies and the structure of the energy complex played a significant role in boosting energy security. The growth of renewables share is accompanied by a reduction in energy dependency, which increases energy security in these countries. (Cergibozan, 2022) has empirically studied the nexus between renewable energy and energy security risk in 23 OECD, focusing on the effect of total renewable energy and renewable technologies separately mainly solar, wind, hydro and biomass on energy security risk. The study shows that there is a positive impact of wind, hydroelectric and total renewables together on reducing energy security risk, while the biomass and solar powers do not show a significant effect on energy security.

In this study, we aim to add to the literature review by focusing empirically on European countries as they are not enough discussed in the literature. In addition, we use energy stock change as a new proxy for energy security, and to the best of our knowledge, it is the first time that it has been employed in this context. Energy stocks can give information about the energy dynamics in an economy. Generally, countries that tend to increase their energy stocks are more exposed to energy security risk and aim to increase them to be protected in short-term market shocks, whilst those reserving less are likely to be surer or satisfied by their energy production.

3. Data and Methodology

3.1. Data

To discuss the dynamics of the energy stocks in Europe, we employed a set of variables that may influence them, collected from different databases mainly the International Energy Agency (see Table 1). The sample employed in this work includes variables for 20 European countries between the available time span from 1992 to 2020. We have chosen the largest 20 European countries¹ in terms of GDP.

To develop our analyses, we started by analysing some of the main variables linked to the energy trends of the various European countries considered:

- *Energy stock changes*: the difference between the initial stock levels on the first day of the year and the last day of the year of the stocks. Energy stocks are the related energy stocks held within a national territory by producers, importers,

1. The countries are as follows: Germany, United Kingdom, France, Italy, Spain, Netherlands, Switzerland, Poland, Sweden, Belgium, Norway, Ireland, Austria, Denmark, Romania, Finland, Czech Republic, Portugal, Greece and Hungary.

Table 1 – Summary of the Variables Considered in the Work (for country details see Table A.1)

<i>Variables</i>	<i>Description</i>	<i>Source</i>	<i>Mean</i>	<i>SD</i>	<i>Min</i>	<i>Max</i>
Energy stock changes	Expressed in Tera-joule (TJ).	IEA*	1,385.5	60020.2	-299,024.6	505,685.4
RE production	Renewable energy production in TJ.	IEA*	314,995.1	307,563	6,472.9	1889,791
Energy production	Total energy production expressed in TJ.	IEA*	2211,906	2635,305	53,244.5	1.18e+07
Energy consumption	Total energy consumption expressed in TJ.	IEA*	2416,222	2452,789	317,702.1	1.01e+07
Energy imports	Total energy imports expressed in TJ.	IEA*	2732,246	2822,925	189,065.3	1.12e+07
Energy exports	Total energy imports expressed in TJ.	IEA*	1324,720	1981,303	8989,084	32,849.5
GDP growth	Annual percentage of GDP growth.	WDI**	1.9	3.1	-11.3	24.4

Notes: * Bought from the International Energy Agency, World Energy Balances (IEA, 2023); ** The World Bank Group. DataBank, World Development Indicators (World Bank, 2023).

Source: Authors' elaborations

energy transformation industries and large consumers. A negative number refers to a stock build while a positive number shows a stock draw (IEA, 2023).

- *Renewable energy production:* is the sum of the production of renewable energy sources including wind energy, solar photovoltaic, solar thermal, hydropower, geothermal, tide energy, biogas, bio gasoline, biodiesel and municipal waste.
- *Energy production:* the total production of primary energy namely hard coal, lignite, peat, crude oil, natural gas liquids (NGLs), natural gas, biofuels and waste. It also involves nuclear, hydro, geothermal and solar as well as heat derived from heat pumps extracted from the ambient environment (IEA, 2023).
- *Energy consumption:* total consumption in end-use sectors and non-energy use excluding energy used for transformation processes and for the internal operations of energy-producing industries. It represents the deliveries made for consumers (IEA, 2023).
- *Energy imports:* the quantities that have crossed the country's national territorial borders whether customs clearance was completed or not. Coal is considered the quantities imported (excluding coal in transit) from other countries without considering the existence or the absence of an economic or customs union

between them. For oil imports, it excludes oil in transit and includes crude oil and oil products imported under processing agreements. Crude oil, natural gas and natural gas liquids (NGL) are reported based on their country of origin, while refinery feedstocks and oil products are recorded based on the country of last consignment. Additionally, imported NGL that is later exported to another country after regasification is treated as both import and export (IEA, 2023).

- *Energy exports*: the quantities that have crossed the country's national territorial borders whether customs clearance was completed or not. Coal is considered the quantities exported (excluding coal in transit) to other countries without considering the existence or the absence of an economic or customs union between them. Oil exports include the crude oil and oil products which are exported under processing agreements. For the imported oil for processing within bonded areas, when it is re-exported, it is recorded as exported from the processing country to the final destination. Additionally, imported NGL that is later exported to another country after regasification is treated as both import and export (IEA, 2023).
- *GDP growth*: refers to the annual percentage increase of Gross Domestic Product at market prices using constant local currency. The aggregates are expressed in U.S. dollars (using constant 2015 prices).

3.2. Methodology

3.2.1. The Variable Selection

As already mentioned, in our analysis we focused on the stock change measure provided by the International Energy Agency for the countries considered over the last two decades. The “stock change” variable, as referenced by the International Energy Agency (IEA), pertains to the variation or alteration in the levels of energy reserves or supplies over a specified period. Specifically, in the context of the IEA's analyses and reports, the stock change provides insights into the net increase or decrease in energy stockpiles, such as oil, gas, or coal, considering factors like production, imports, exports, and consumption. A negative number refers to a stock build while a positive number shows a stock draw (IEA, 2023). Following these indications, our interest was therefore to understand in which circumstances, for each country considered, there was an increase or decrease in energy stocks. Consequently, we decided to construct a dichotomous dependent variable which, starting from the sign of the stock changes variable (*Schng*), represents the possible underlying propensity towards a decrease in energy stocks (*Schng*=1) that fall along a continuum related to the level of energy security and to test its dependence with five variables as explanatory variables as follows:

- *Energy production / Energy consumption*: the ratio between energy production and consumption used as an indicator to highlight the ability of a country to meet its energy needs by consuming what it produces. A high value indicates that the country produces more than it consumes and its domestic production satisfies its energy needs while a low ratio suggests that the country's energy sufficiency is low and may rely on foreign sources to fulfil its energy necessities.
- *Energy imports / Energy consumption*: the fraction between energy imports and energy consumption specifies the share of energy needs of a country that are met through importation compared to its energy consumption. It highlights the energy dependency on external energy imports: a low share means less dependency on international energy market and higher energy security.
- *Energy exports / Energy production*: the ratio between energy exports and energy production represents the share of the total energy production of a country that is exported to other countries. A low value implies that the country uses its produced energy domestically and it therefore has a limited economic interest on the international energy market as supplier.
- *Renewable energy production / (Energy production + Energy imports – Energy exports)*: refers to the share of renewable energy production in total energy supply. It indicates the proportion of the energy generated from renewable resources compared to overall provided energy. This represents our variable of greatest interest since it could allow us to understand the relationship between renewable energy and the mitigation of energy risk.
- *GDP growth*: we have decided to also include the variable GDP growth to take into account possible influences on economic growth which may be different for the various countries.
- *Country*: we also considered a fixed effect for each country by introducing an additional multinomial variable.

3.2.2. The Model

The research idea of this contribution is to investigate under what conditions the probability that a country's energy stocks are reduced.

Starting from what was presented above, our objective is to verify the following hypotheses:

- *H1: High capacity to meet internal energy demand through internal production can guarantee the stability of the internal market, and therefore makes high energy stocks less necessary.*
- *H2: Country's greater exposure to international energy markets leads to maintaining high energy stocks.*

Table 2 - Summary of the Variables Used in the Empirical Analysis

Variables	Description
Stock changes: (Schng)	Dichotomous variable referred to Energy stock changes: “0” refers to a stock build while “1” to a stock draw.
% of RE in total energy supply (REshare)	Renewable energy production / (Energy production + Energy imports – Energy exports)
Energy auto-sufficiency (EAS)	Energy production / Energy consumption
Energy demand from foreign markets (EDF)	Energy imports / Energy consumption
Energy supply to foreign markets (ESF)	Energy exports / Energy production
GDP growth (GDPg)	Annual GDP growth
Country	Multinomial variable: Germany, United Kingdom, France, Italy, Spain, Netherlands, Switzerland, Poland, Sweden, Belgium, Norway, Ireland, Austria, Denmark, Romania, Finland, Czech Republic, Portugal, Greece and Hungary

Source: Authors’ elaborations

- *H3: Greater energy production from renewable sources guarantees a more secure source of supply and can induce countries to reduce energy stocks.*
- *H4: Economic growth trends can lead countries to accumulate energy stocks which can be useful in guaranteeing the growth process.*

To test the hypotheses, we decide to use a probit analysis. Probit analysis is particularly appropriate when trying to estimate the effects of one or more independent variables on a binomial dependent variable. Probit regression assumes that the relationship between the predictors and the probability of the response variable can be modelled using the cumulative distribution function (CDF) of a normal distribution. In other words, probit regression assumes that the probability of the response variable being equal to 1 can be modelled using a normal probability density function and that the values of the predictor variables determine the mean and standard deviation of the distribution (Hong, *et al.*, 2022). We use probit regression to model the relationship between the binary variable *Schng* and the predictor variables of Table 2 and its general specification is as indicated in the following equation:

$$Pr (Schng_{it} = 1) = \Phi(\beta_0 REshare_{it} + \beta_1 EAS_{it} + \beta_2 EDF_{it} + \beta_3 ESF_{it} + \beta_4 GDPg_{it} + u_i + \varepsilon_{it}) \quad [1]$$

Where $Schng_{it}$ is the binary dependent variable for country i and year t , [Equation 1] refers to the cumulative distribution function of a standard normal distribution, $\beta_0, \beta_1, \beta_2, \beta_3, \beta_4$, are the coefficients to be estimated, u_i , indicates the country fixed effects and ε_{it} is the random error.

4. Results and Discussion

Although the general purpose of this analysis is to verify the various hypotheses of the model, the main objective of this study is to understand what effect has a greater production of renewable energy on changing the amount of energy stocks owned annually by each country, in particular, we intend to perceive whether a greater production of renewable energy can increase the probability that the stock decrease and therefore obtain a value of “1” for the dependent variable. To do so, we developed a Probit analysis using Mathematica® on our data and the fitting results are shown in Table 3.

As can be noticed from the results, both variable Energy auto-sufficiency (EAS) and variable GDP growth (GDPg) are not significant in our analysis, whereas the variables related to the external market relationship namely the energy demand from foreign markets (EDF) and the energy supply to foreign markets (ESF), especially the variable measuring the amount of renewable energy produced in relation to all available energy (REshare), are significant.

The lack of significance of the variable Energy auto-sufficiency (EAS) would seem to *deny Hypothesis H1* and, at first glance, it might appear uninteresting. In our opinion, however, it is very significant and reflects an important signal of the energy behaviour of the various countries. In fact, it tells us that the “current” ability to satisfy internal demand with internal production does not seem to sufficiently “ensure” the country systems. This aspect is indeed intriguing and has also been emphasized by several analyses (Dyatlov, *et al.*, 2020), which underscore the fact that in certain countries where new initiatives for diversifying energy supply have been initiated, they stem from concerns regarding the lack of long-term guarantees offered by the current production capacity.

For the variables related to the external market relationship, it is interesting to note that the sign of the coefficients associated with the interaction with the external market is negative for both variables (-1.79274 and -0.757505): this confirms that greater exposure to international energy markets induces individual countries to keep high values of energy stocks instead of reducing them in order to contain the risk that may arise from price volatility. *This affirmation verifies our Hypothesis H2.*

Indeed, when there is a price spike in the international market, energy importing countries (for example: Germany, Italy, France, Netherlands, United Kingdom and

Table 3 – Empirical Results

Probit Results Cox&Snell PseudoR2 = 0.3132 Pearson ChiSquare = 638.5 Dependent variable: Stock changes				
	<i>Estimate</i>	<i>Standard Error</i>	<i>z-Statistic</i>	<i>P-Value</i>
REshare	3.079	1.566	1.966	0.049
EAS	-0.106	0.186	-0.572	0.567
EDF	-1.793	0.510	-3.517	0.001
ESF	-0.757	0.288	-2.634	0.008
GDPg	-0.020	0.018	-1.151	0.249
<i>Country effect</i>				
Austria	0.883	0.606	1.458	0.145
Belgium	1.631	0.662	2.465	0.014
Czech Republic	0.840	0.504	1.668	0.095
Denmark	1.447	0.616	2.349	0.019
Finland	0.927	0.626	1.480	0.139
France	1.470	0.578	2.540	0.011
Germany	1.917	0.563	3.403	0.001
Greece	2.036	0.687	2.964	0.003
Hungary	1.190	0.541	2.198	0.028
Ireland	1.772	0.552	3.207	0.001
Italy	1.748	0.553	3.157	0.001
Netherlands	2.730	0.941	2.901	0.004
Norway	-0.524	2.058	-0.255	0.799
Poland	0.710	0.456	1.558	0.119
Portugal	0.947	0.610	1.550	0.121
Romania	1.031	0.484	2.128	0.033
Spain	1.728	0.646	2.673	0.007
Sweden	0.759	0.678	1.118	0.263
Switzerland	1.315	0.566	2.322	0.020
UK	1.286	0.524	2.453	0.014

Note: * The time span considerate in the analysis is 1992-2020.

Source: Authors' elaborations

Spain (IEA, 2023)) try to use their reserves of energy to stabilise domestic prices and for them it is important to have an abundant energy stock to better respond to the market. For these countries, it is important also to diversify their energy mix and include alternative resources as a hedge against price volatility and market pressures. In the opposite case, energy exporting countries tend to accumulate stocks to be able to respond promptly in case of a spike in external market demand. This dynamic is well recognized within the EU and over the years multiple initiatives have been put in place to address the volatility of the energy market. As a matter of fact, to ensure a consistent and stable energy supply across member states, the EU has established directives regarding energy emergency stock levels (Directive 2009/119/CE) (European Union, 2009b). These directives mandate that member countries maintain a minimum level of oil and petroleum product reserves equivalent to at least 90 days of average daily net imports or 61 days of average daily inland consumption, whichever is greater. Furthermore, the EU specifies that these emergency stock levels should be accessible and deployable within a short notice period. Member states must also regularly report their stock levels to the European Commission, ensuring transparency and adherence to the established norms. The rationale behind these directives is multifaceted. Firstly, it aims to mitigate the potential impacts of sudden energy supply disruptions, whether due to geopolitical tensions, natural disasters, or other unforeseen events. Secondly, it underscores the EU's commitment to ensuring energy security, promoting stability in energy markets, and safeguarding the interests of both consumers and businesses. Also, energy prices started rising in the EU well before the invasion of Ukraine and the Commission reacted to growing pressure to act by adopting guidance to Member States in the form of a Communication in October 2021 entitled “Tackling rising energy prices: a toolbox for action and support”.

The positive sign of the parameter linked to the portion of renewable energy out of the total available energy (Reshare) *confirms the Hypothesis H3* and responds to the question to which this contribution refers. In fact, it shows how a greater percentage of available renewable energy is more likely to lead to a reduction in energy stocks. It is useful to remember in this case how this result is in line with European directives regarding the energy transition towards renewables.

The commitment of Europe to its energy shift is not related to recent conditions and the development of renewable energy has been at the core of its energy policy for many years. Between 2001 and 2009, the European Union adopted a set of initiatives to impose on its countries the increase of renewable sources used to produce energy, to raise the share of renewables in electricity production (Directive 2001/77/EC), to adopt renewable fuels including biofuels in the transport sector (Directive 2003/30/EC) and other renewable resources in different sectors such as heating and cooling (Directive 2009/28/EC) (European Union,

2001; 2003; 2009a). In 2018, another action known as the Renewable Energy Directive suggested that by 2030, at least 32% of the energy produced in the EU has to be generated from renewables.

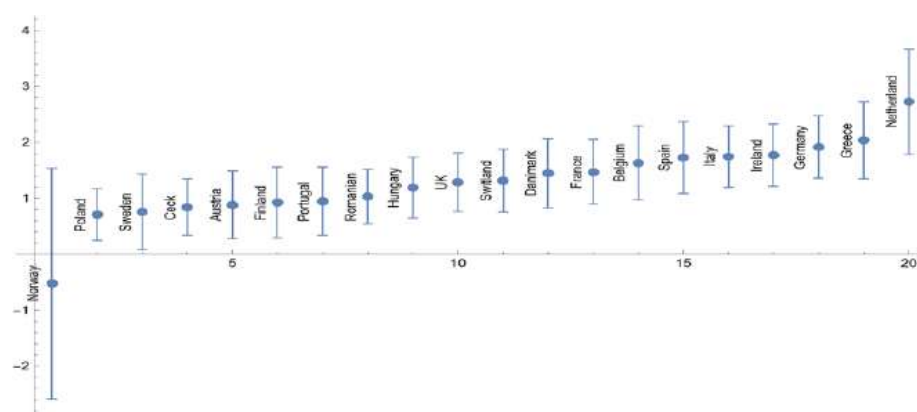
Finally, the findings of our analysis do *not confirm Hypothesis H4*. In this case, however, the result could be connected to the variability of the data which could lead to a distortion of the result. To investigate this possibility and evaluate the robustness of the results, we first repeated the analysis on a subsample relating to narrower time windows and replacing the variable GDP growth by GDP growth per capita. The results confirmed what was obtained before and led to deeper reflections on whether there is indeed a mechanism that can link the growth dimension, possibly with different indices, to that of energy security.

5. Country Fixed Effects

The results deriving from the contribution of country fixed effects also deserve careful discussion. Considering the country fixed effects, it is noteworthy how the parameters related to the country fixed effects are positive, except in the case of Norway for which the parameter, although the estimate has a very large standard error, takes on a negative value (see Figure 1).

This negative value is explained by the fact that, within our panel data, Norway is a unique case in which the value of energy production is much higher than

Figure 1 – The Estimated Parameters for Each Country (u_i)



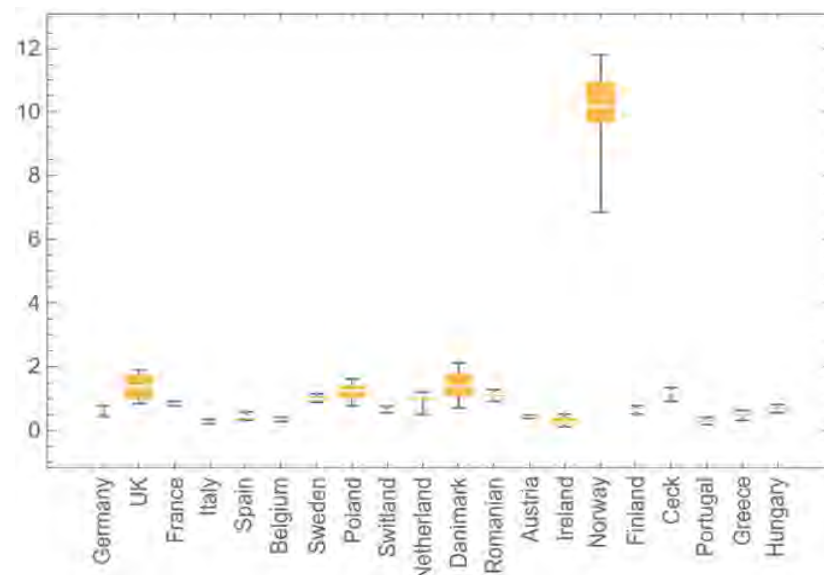
Source: Authors elaborations on values u_i

domestic demand (approximately 5 times the average value of the other countries in our sample, see Figure 2) and in this case, the level of energy risk appears to be considerably low, likely not linked to stock levels at all.

Norway is a remarkable and unique example of energy self-sufficiency in renewable energy and it is more energy secure than almost any other country. Between 1995 and 2020, Norway registered a power surplus and became one of the most energy independent countries, being the world's fifth largest petroleum exporter and seventh largest hydropower producer (Hansen, Moe, 2022).

Excluding Norway, we can identify three distinct groups of countries depending on the parameter values through the definition of some merely symbolic thresholds. The first group of countries is made up of six countries namely Poland, Sweden, Czech Republic, Austria, Finland and Portugal, for which the estimated best fit parameter takes on a value less than 1; for these countries, we can define a general low propensity towards a decrease in stocks. For the countries of a second group which is composed of Romania, Hungary, Denmark, France, UK and Switzerland, the estimated value of the parameter varies within a range of 1 and 1.5; for these countries, we can define a general moderate propensity towards a decrease in stocks. Finally, for the countries belonging to the last group, the estimated parameters are greater than 1.5 with a maximum value of approximately 2.7 for the Netherlands. These countries have a greater propensity

Figure 2 – Energy Auto-sufficiency for Each Country



Source: Authors elaborations

to decrease energy stocks probably because of a progressive transition towards the diversification of energy sources. This last result is interesting and deserves further analysis which could provide useful indications at a macroeconomic level on the nature of any exogenous or endogenous causes that may be at the basis of this variability.

6. Conclusion

In the present study, we were interested in examining how an extensive production and use of renewable energy may affect the energy stocks dynamics in an economy. We mainly focused on 20 European countries as Europe is one of the most exposed regions to energy security risks. The European Union's economy is reliant on fossil fuels, which account for nearly three-quarters of its total energy consumption. Fossil energy is largely imported: the EU's share of global fossil fuel demand stands at 8%, compared to its share in global production of 0.5% for oil and 1% for gas, respectively.

Using a panel sample for the period between 1992 and 2020, we applied a Probit estimation model considering the sign of energy stock change as the binary dependent variable and the share of renewable energy in total energy supply as the main independent variable. We included also other energy related variables: the energy auto-sufficiency and two variables related to the external market relationship which are the energy demand from foreign markets and the energy supply to foreign markets.

We tested the relationship between all variables in the model and we concluded that whether the country is an energy supplier or demander, the exposure to foreign energy markets is highly linked to energy security risks as the coefficients of the energy demand and supply are both negative, which means that those countries tend to increase their stocks to overcome the market risks.

On the other hand, the share of renewable energy in the total supply is significant and positive, suggesting that countries having an important share of renewables in their energy supply are likely to decrease their energy stocks as they are not much exposed to market fluctuations. Expectations of a demand decrease can heighten uncertainty about the future returns on fossil fuel investments, thereby reducing their volume. A decline would manifest in reduced supply and increased prices. However, other supply channels might lead to price decreases. For instance, producers might opt to expedite the exploitation of their reserves, resulting in increased supply and decreased fossil fuel prices. Similar effects – namely, increased investments and reduced costs – might also arise from technological innovations related to fossil fuels, such as carbon capture and storage.

So, renewable energy appears to be an important solution for European countries to gain energy independence and security and considering that, they should improve energy policies and implement renewable plans to accelerate their transition towards green powers.

In this work, we have provided an overview of energy dynamics in European countries focusing on their energy stocks in relation to renewable energy deployment. However, there is a potential for future research to extend our analysis to add other countries beyond Europe. In order to focus on different geopolitical contexts, we aim to provide a better understanding of global energy stocks and the energy transition landscape at the international level.

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Sommario

Dinamica delle scorte energetiche in Europa: un'analisi nel contesto della transizione energetica

Negli ultimi tempi, il crescente rischio energetico dei paesi dovuto alle tensioni geopolitiche internazionali ha accentuato le problematiche relative all'uso di combustibili fossili e le ripercussioni sulle economie hanno spinto verso una rapida transizione verso

fonti energetiche sostenibili come le rinnovabili. La produzione di energia da fonti rinnovabili è diventata una indubbia priorità, specialmente nei paesi avanzati come quelli europei che sono, ancora oggi, fortemente dipendenti dai combustibili fossili, nell'idea di attenuare il rischio energetico. Una maggiore produzione di energia rinnovabile dovrebbe consentire infatti all'economia europea di affrontare più agevolmente un rincaro dei prezzi energetici e una restrizione dell'offerta dei combustibili fossili. Tuttavia, le energie rinnovabili presentano anch'esse svantaggi, quali l'intermittenza nella produzione e il fabbisogno di materie prime necessarie per la costruzione degli impianti. Questo articolo si propone di analizzare il ruolo delle energie rinnovabili in Europa, studiando, attraverso un modello Probit, come le varie dinamiche energetiche dei paesi possano influenzare le riserve di energia dai vari paesi. I risultati mostrano che un incremento nell'uso di energie rinnovabili porta a ridurre le riserve energetiche, di contro una maggiore presenza nei mercati globali può aumentarle. Infine, basandosi sui risultati ottenuti, i paesi sono stati classificati in tre categorie secondo la loro tendenza a ridurre o meno le riserve energetiche.

Appendix

Table A.1 – Means, Maximum and Minimum Values for Each Variable for Each Country, 1992-2020

Country	Stock Changes			RE Production			Energy Production		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Germany	35533.24	-299024.56	230432.07	889759.80	212248.20	1889790.86	5631431.57	4045733.32	7794023.35
United Kingdom	32111.97	-189247.91	505685.45	223079.62	42508.99	687714.96	8019592.47	4475511.6	11790263.1
France	-11157.87	-200575.33	111877.43	782264.38	628825.96	1055806.65	5473429.82	4684462.68	5819910.04
Italy	-3172.76	-192781.76	108653.60	628411.99	267144.20	1041004.5	1304292.75	1059992.10	1539343.67
Spain	-1470.39	-112848.62	146928.44	451452.99	213876.79	782052.62	1370295.01	1262357.83	1476089.45
Netherlands	-10158.01	-130001.61	79869.94	110159.18	31235.60	285080.4	2502314.30	1140495.89	3131350.43
Switzerland	5454.36	-8083.34	33920.87	186301.86	148891.66	222543.95	493938.67	428023.93	546670.34
Poland	-22646.66	-174511.70	107385.04	243028.85	56753.99	511632.02	3317894.88	2422563.99	4349069.12
Sweden	-975.15	-130211.99	85704.60	618617.40	460277.40	843279.82	1387885.65	1227354.37	1553774.74
Belgium	-2810.82	-38128.32	52077.03	63726.51	13626.99	160860.68	571013.93	449307.59	668976.98
Norway	-5813.92	-77460.81	87054.75	503857.47	417834.6	598466.83	8474639.51	5002329.67	9915020.44
Ireland	154.88	-35402.38	32082.92	22268.14	6472.88	65062.29	110821.51	53244.49	209159.47
Austria	-490.87	-106493.13	48323.23	314649.08	208927.20	423223.28	434727.35	340643.30	530130.61
Denmark	686.72	-60236.89	50851.56	99858.92	43192.80	167538.39	836706.95	385790.01	1308726.17
Romania	686.72	-56424.16	44198.21	186934.47	66291.60	255210.11	1209539.53	937327.64	1693785.98
Finland	13481.56	-96320.47	86167.02	348173.19	212674.80	481268.64	665241.38	467634.47	822591.19
Czech Republic	3663.24	-57943.72	76867.1	112152.82	47757.60	207227.28	1345075.91	991379.58	1723507.64
Portugal	-39.65	-20675.7	36688.47	182488.86	119287.40	248591.90	186882.37	123080.42	254419.45
Greece	-1511.89	-44166.38	80826.56	76185.11	46249.60	118028.34	381334.85	190709.95	438622.11
Hungary	-5629.39	-112442.57	55202.35	76032.36	33065.80	138750.96	499688.54	428578.15	614946.28

Country	Energy Consumption			Energy Imports			Energy Exports		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Germany	9616169.22	8955070.99	10135123.5	9964868.57	7919295.25	11216628	1511259.9	710480.72	2540401.8
United Kingdom	5807995.05	4774851.22	6341465.98	4881078.31	3104474.73	6971992.56	3885570.34	2724007.82	5421132.12
France	6563809.61	5777900	7064125.17	6554297.00	5339183.53	7521777.14	1229611.23	837947.30	1597543.16
Italy	5246566.60	4498109.71	5915407.07	6784612.46	5485335.58	8044942.00	1068024.79	729799.49	1396980.02
Spain	3455625.24	2544476.15	4266733.92	4661820.36	3048456.62	5720997.07	690293.11	297735.99	1364112.66
Netherlands	2477465.78	2256918.86	2732261.54	6216008.06	4224289.29	8625565.11	4903683.55	3480540.25	6728642.18
Switzerland	801591.571	720001.98	860696.83	739525.93	622273.34	816843.38	131700.77	89426.68	155482.19
Poland	2745054.45	2397955.33	3288439.32	1611228.10	859578.28	2685069.76	796306.88	534684.20	997873.19
Sweden	1422507.98	1329976.47	1542490	1325529.89	1128871.98	1528932.62	552312.85	386824.74	879647.40
Belgium	1663156.63	1349099.61	1789743.39	3168257.77	2536660.13	3677122.83	1118945.44	818630.14	1591070.99
Norway	831533.29	713074.75	892610.18	294733.26	189065.29	486669.92	7584920.65	4228435.85	8989083.78
Ireland	430105.84	315729.31	527161.21	521790.81	318495.04	651536.89	56365.67	29223.38	84344.58
Austria	1052063.49	827662.7	1173748.57	1103656.98	778687.09	1376803.65	226950.78	50892.09	580660
Denmark	595417.28	544055.92	633771.08	682594.19	554451.77	790773.02	678043.2	301536.05	1019341.73
Romania	622981.56	428061.04	1140236.95	622981.56	428061.04	1140236.95	190878.44	97066.80	268182.39
Finland	1028966.93	924270.43	1114229.47	1010840.6	818682.39	1199666.3	269816.70	72406.69	427749.99
Czech Republic	1134482.02	1054246.48	1380791.49	835274.10	640385.40	1003808.03	357424.49	231256.94	610281.28
Portugal	722629.43	560793.61	856631.20	961445.60	721658.89	1165965.91	160392.93	70342.80	335110.89
Greece	736263.40	606827.97	913908.24	1215049.63	836994.25	1630832.22	384446.08	139887.56	860732.97
Hungary	776817.49	712677.17	866180.12	772270.39	532831.37	1219840.96	167677.61	51796.30	440835.93

Source: Authors' elaborations

Foreign Direct Investment (FDI) Impacts on Energy Poverty in African Countries

BY EMNA KANZARI,^a STEFANO FRICANO,^b GIOACCHINO FAZIO,^c AND JING YU^d

Abstract

Most of the people lacking access to energy are mainly concentrated in Africa, representing serious challenges to its socio-economic development. FDI can help alleviate energy poverty in Africa through infrastructure development, technological advancement and economic growth channels. However, the complex economic system within which it operates requires increased attention.

1. Introduction

In today's technologically advanced world, energy represents the lifeblood that powers every single aspect of the life of human beings, starting from basic human needs such as heating and cooking to very advanced innovation and research. Despite the remarkable technological development, that the last century has witnessed, an important number of people around the world still live without access to energy and still suffer from energy poverty. Energy poverty is one of the serious challenges that the international energy system faces. It leads to poverty, hunger, poor health and low quality of education, and hinders innovation, industry and infrastructure development, spreading consequently inequality gaps. Hence, access to modern, reliable and affordable energy services offers more socio-economic opportunities by enhancing the use of basic and advanced electronic devices for example, which are necessary for extending daily activities during the night and improving the quality of education, health and work (Sambodo & Novandra, 2019).

However, enhancing economic growth, infrastructure and advanced technological levels is a key factor in mitigating energy poverty. Foreign direct investment (FDI) is known for being a main driver of these factors, thus FDI can represent an important opportunity to alleviate energy poverty through these three channels.

2. Energy poverty in developing countries: the case of Africa

Despite its relevance, access to basic energy is still lagging amid the international efforts to provide energy services for all. According to the Energy Progress Report 2023, despite that access to electricity raised globally between 2010 and 2021, there are still 675 million people around the world living without access to electricity in 2021. Most of these people are concen-

trated in the African continent with around 80% of this number is registered only in Sub-Saharan Africa. Due to its accelerating population growth, the sub-Saharan region is home to 567 million people lacking access to electricity, accounting for almost half of the regional population, with the highest numbers recorded in Nigeria, the Democratic Republic of the Congo and Ethiopia. On the other hand, North Africa has shown a significant decrease in its access deficit with a regional access rate of 94% (WorldBank, 2023).

Paradoxically, Africa is known for holding almost all types of natural and mineral resources, both renewables and non-renewables that are more than sufficient to meet its domestic needs. According to the United Nations Environment Programme, around 30% of the world's mineral reserves, 12% of the world's oil and 8% of the global natural gas are registered in the continent (UNEP, 2024). In addition, Africa is home to a high and diversified potential of renewable resources including solar, wind, hydropower and bio-energies which are fundamental to providing clean and modern energy for its population.

2.1 FDI in Africa

The natural resources sector not only can enable the continent to cover its needs for energy but also is one of the main drivers that can play a vital role in attracting foreign investors. In fact, like many developing regions, Africa has become recently one of the most attractive destinations for foreign investments due to its vast natural resources and also for being a growing consumer market (Gong, et al., 2023).

It is commonly understood that FDI is beneficial for host economies by boosting their economic growth, employment level (by creating new job opportunities), domestic investment, infrastructure, human capital development and productivity through technology and knowledge transfer (Zhang, 2021). In addition, FDI can contribute to ending poverty and its forms including energy poverty which can be reduced by increasing electricity generation access by investing directly in power generation and infrastructure (Aluko, et al., 2023). FDI can bring new technologies to local firms and transfer to them new knowledge. By imitating technologies and know-how from foreign firms and taking advantage of their expertise, local enterprises learn new ways to generate electricity and thus increase electricity access (Hu, et al., 2021; Aluko, et al., 2023). Accordingly, foreign capital has a strong influence on

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electricity access levels in hosting countries (Aluko, et al., 2023).

According to the United Nations Conference on Trade and Development UNCTAD statistics, the foreign direct investment inflows to Africa have seen a tremendous increase from nearly \$5 billion between 1991 and 1995 to around \$53.5 billion between 2018 and 2023. To date, an important part of these investments is mainly received from five countries namely France, the United Kingdom, the Netherlands, the United States and China. Despite that Western countries such as France and the United Kingdom have been for a long time the first investors in Africa, China has become its leading trading and investment partner, increasing its stock by more than 50% from 2013 to 2017 and surpassing some Western partners (Hu, et al., 2021).

2.2 Chinese FDI in Africa

In 2016, China topped the list of all foreign investors in the continent, which highlights the Chinese interest in investing in Africa. According to the China Statistical

Yearbook, the Chinese FDI stock in Africa reached \$40.9 billion in 2022 and almost 90% of total Chinese outwards were destined to Sub-Saharan Africa between 2003 and 2022. Like its Western partners, China's focus has been for a long time on the natural resource extractions sector, which has been the top recipient sector for years and in 2015, it accounted for 27.5% of the total Chinese FDI in the continent. After 2015, the construction sector has gained more importance and has topped all recipient sectors. In 2022, the construction for infrastructure sector received the highest share of Chinese FDI, representing 33.3% of total China's investment stock (CARI, 2024). In recent years, Chinese firms have heavily invested in electricity and transport sectors mainly in ports and roads construction and maintenance, hydropower stations, power grids, hospitals and other activities such as the nuclear power project in Kenya, the first modern tramway in Sub-Saharan Africa, in addition to Tazara railways linking Zambia with the Dar es Salaam port in Tanzania (Akinshipe & Aigbavboa, 2022).

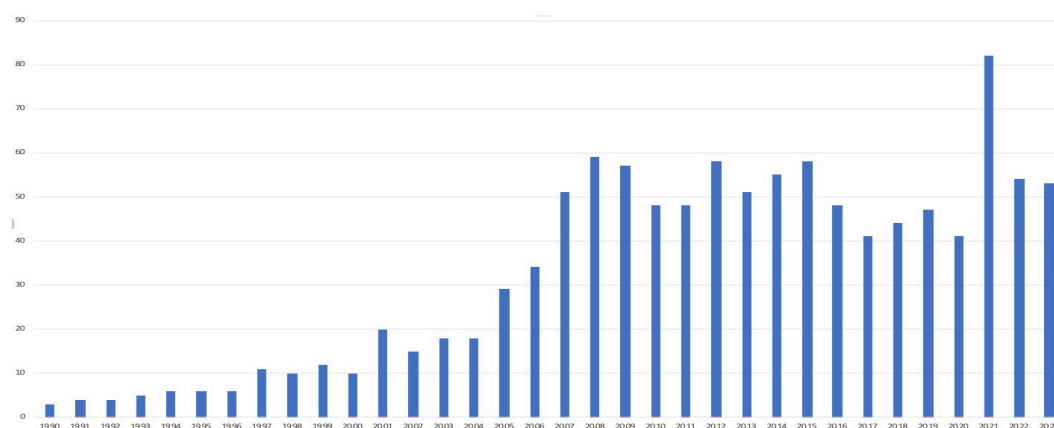
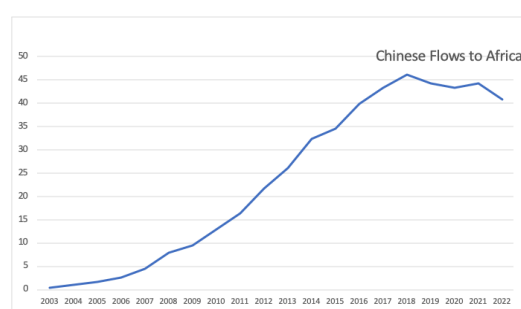
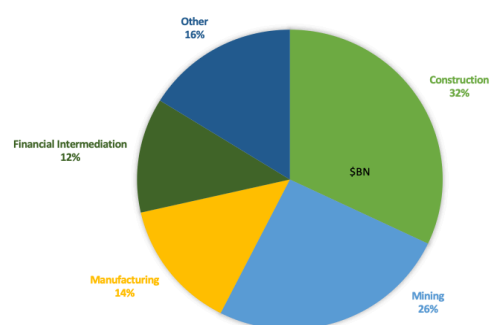


Figure 1: FDI flows to Africa (1990-2023, in billions of USD)
Source: The authors, based on data from UNCTAD statistics.



A: Chinese FDI to Africa (2003-2022, in billions of USD)

Figure 2: Chinese FDI flows to Africa
Source: The authors, based on data from UNCTAD statistics.



B: Chinese FDI to Africa by sector (2013-2022, in billions of USD)

3. FDI: a key factor to reduce energy poverty

Multinational firms can increase electricity connectivity through different channels. Firstly, they can raise energy access by developing and modernising electricity infrastructure since it is necessary for the investors' activities and thus expand energy generation. Foreign investors can directly develop infrastructure and new grids to provide the energy needed to facilitate their business activities (D'Amelio, et al., 2016). In addition, FDI can bring new technologies to local firms and transfer to them new knowledge. By imitating technologies and know-how from foreign firms and taking advantage of their expertise, local enterprises learn new ways to generate electricity and thus increase electricity access (Hu, et al., 2021; Aluko, et al., 2023). Accordingly, foreign capital has a strong influence on electricity access levels in hosting countries (Aluko, et al., 2023).

(D'Amelio, et al., 2016) has investigated how FDI and multinational firms from 83 countries could promote electricity access in 15 host countries in Sub-Saharan Africa between 2005 and 2011. Relying on different econometric techniques mainly the system Generalised Method of Moments GMM and Least Square Dummy Variable, they concluded that the presence of FDI increases electricity access, in particular, in countries characterised by weak institutional quality. According to their analyses, FDI is associated with the development of electricity infrastructure that is necessary for their operations which also helps them gain legitimacy with the stockholders in the local economies. Similar conclusions were found by (Garrone, et al., 2019) in their study on the effects of multinational enterprises on energy poverty in developing countries, specifically in Sub-Saharan Africa. The authors applied the system GMM to a sample of 73 investing countries and 15 host Sub-Saharan countries over the period 2005-2011. Their empirical results pointed out that the host countries affected by poor institutional framework have seen their electrification levels positively impacted by FDI coming from countries that are institutionally closer to them. (Nguea, et al., 2022) have extended the analyses on the relationship between foreign capital and electricity access of the local population to more African countries and a longer period (2000-2017), using the same technique, the system GMM which is suitable for panel data analyses. The findings reveal that while foreign aid decreases electricity access in Africa, FDI increases the share of the population that has access to electrification. However, these inflows do not seem to have a positive impact on reducing the urban-rural disparities in electricity access. More recent work on the same relationship conducted by (Aluko, et al., 2023) emphasised the importance of FDI in lighting up African countries between 2000 and 2017. Not only that, but they also highlighted how the interaction between governance and FDI could influence electricity access in the studied countries. Mainly, FDI has a higher effect on the level of electrification in countries with lower levels of governance.

In an attempt to study the drivers of energy poverty reduction and specifically the role of natural resources

in Sub-Saharan Africa, (Nkoa, et al., 2023) employed the pooled Ordinary Least Squares (OLS) and the difference GMM on a sample of 45 African countries between 1997 and 2018. Their conclusions showed that natural resources do not increase electricity access, while per capita income, secondary education and employment help in reducing energy poverty by increasing electricity access to the local people. FDI also plays a vital role in providing electricity in Africa, particularly in rural areas. Employing different determinants including FDI in their analyses, (Khan & Majeed, 2023) focused on the financial sector development impact on energy poverty in developing countries. To empirically investigate the relationship between the different variables, they used several econometric methods such as pooled OLS, fixed and random effects and GMM. They concluded that financial development is important to alleviate energy poverty in the 110 studied economies between 1990 and 2020. The same positive impact was also found between FDI inflows and electricity access. According to the authors, foreign capitals are accompanied by advanced technology transfer that may reduce energy intensity and thus decrease energy poverty. Considering a more comprehensive financial framework, (Ajebe, 2024) examined the nexus between financial resources, energy poverty and CO2 emissions in 54 African countries. The study contributes to the literature on the relationship between FDI and energy poverty and found out that FDI, together with financial development and official development assistance, plays a significant role in the energy landscape in Africa and has a strong connection between them, energy poverty and GHG emissions.

The other channel through which FDI can contribute to energy poverty reduction is economic growth. It is agreed that FDI is an important driver for economic development through the transmission of capital and funds, access to new markets, expansion of production and technology transfer (Sunde, 2017). Moreover, higher economic growth is generally associated with higher government spending on energy infrastructure in different areas. In addition, economic growth may result in an improvement in income levels, and thus householders are likely to choose cleaner and sustainable sources of energy. Hence, FDI can promote access to energy through its effect on economic growth (Nguyen & Su, 2022; Nguea, et al., 2022).

4. Challenges

Considering the previous affirmations, FDI, being an importer of new technologies, able to create new job opportunities and a contributor to the host economy, represents a key driver in promoting energy access and reducing energy poverty. However, it is extremely crucial to join the debate on the FDI and energy poverty relationship, including a comprehensive empirical model to help policymakers, particularly in Africa.

The goal is to explore how African countries should structure their policies regards FDI regulations to reduce the number of people living without access to energy. This requires to carefully balance the timing of

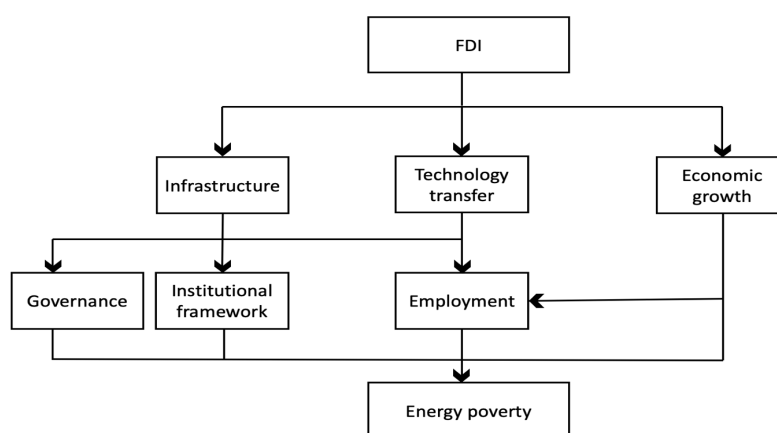


Figure 3: FDI and energy poverty nexus
Source: The authors, based on the literature review.

these interventions with their efficiency. Specifically, it is important to clarify the priority between addressing energy poverty in the short term or pursuing a longer-term strategy that achieves a higher percentage of people lifted out of poverty.

Moreover, policymakers must assess the relative impact of various channels through which FDI can alleviate energy poverty. Some channels may offer quicker solutions with immediate benefits, while others could require more substantial, long-term improvements. Therefore, finding an effective balance between short-term gains and long-term sustainability is essential to ensure both immediate relief and long-term progress in reducing energy poverty across Africa.

It becomes highly important to deepen the understanding of the economic processes that deeply connect different dynamics. Accordingly, further econometric analysis is needed to explore the conditions and the relations allowing to identify the balance between long-term and short-term investments. Also, it is required a deep understanding of the priorities of each territory, in order to better direct FDI.

5. Conclusion and Proposition

Understanding the relationship between foreign investments and the reduction of energy poverty in developing countries is crucial for driving sustainable progress. Foreign investments, particularly in energy infrastructure, have the potential to transform economies by providing access to clean, affordable, and reliable energy sources. This access can empower communities, improve living standards, and foster economic growth. However, the complexity of this relationship demands a deep, interdisciplinary exploration to assess both the positive impacts and the challenges that may arise.

A **call for research** is being proposed to establish a network of complementary studies aimed at collectively addressing the multifaceted connections between

foreign investments and the reduction of energy poverty. By gathering diverse perspectives—spanning fields such as economics, environmental science, policy analysis, and social justice—this initiative seeks to create a comprehensive body of work.

The proposed goal is to compile these studies into a unified framework that, like pieces of a puzzle, will offer a clear and holistic understanding of how international funding can effectively mitigate energy poverty. This initiative will invite scholars and experts to contribute their research

and insights, fostering collaboration across disciplines. The outcome of this collective effort is envisioned to inform and guide future policy-making and investment strategies, ultimately promoting equitable and sustainable development in regions most affected by energy poverty.

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