Climate Change and Economic Development in Africa

A Systematic Review of Energy Transition Research

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Cover Image: Johannesburg, South Africa

CLEAN AIR TASK FORCE

Abstract

African countries face a dual challenge of building broad-based prosperity for their citizens amidst the threat of climate change and the recognition of the need for global greenhouse gas emissions reductions. While these two issues are increasingly discussed in tandem in policy circles, the research has typically considered them separately, resulting in energy decarbonization plans that fail to consider critical development needs and contribute to persistent energy poverty. This paper reviews the state of knowledge on energy transition modeling and projections in Africa, with special attention to development imperatives and the commitment to eliminating greenhouse gas emissions. We analyzed 156 peer-reviewed research papers that cover part or the whole of Africa, concerned with the issue of the energy transition and that are model-based or scenario-based. Our analysis revealed that (i) Energy transition modeling is a recent but fast-growing phenomenon in Africa, with over 90% of papers completed after the Paris Agreement in 2015 (ii) despite the complexities involved, only a handful of scenarios are often presented, largely focused on 2030 or 2050 time horizons, with little to no considerations of social and political considerations that may hinder implementation, (iii) projections of energy mix and emissions pathways are the key objectives in general, with only 10% of the papers reviewed considering development as a central outcome, (iv) technologies such as carbon capture, nuclear, hydrogen, or electrofuels, that stand to play a vital role toward a low or zero carbon transition are among the least considered, and (v) nearly two-thirds of the research was produced without an author based on the African continent. We discuss the significance of these findings and reflect on ways to further enhance knowledge leadership to guide a more practical approach to tackling climate change and promoting socio-economic development in Africa.

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SECTION 1

Introduction

In the last quarter century, the African continent has seen a significant uptick in economic growth and improved governance. It is now usual for African countries to feature among the fastest-growing economies in the world. Varying levels of improved human development have accompanied this economic growth, and the poverty rate has fallen from 53% in 1990 to 39% in 2019.[5] Poverty remains high, however, and even those who no longer fall below the poverty line are vulnerable and far from reasonable aspirations for human prosperity. Scholars have debated ways to sustain growth and structural transformation in Africa. One focal point of this debate is whether the fast-growing service sector, often marked by low productivity jobs, can carry the continent much further. While some argue that Africa cannot escape traditional manufacturing as a pathway to development, as it has been in most parts of the world (Abreha et al., 2021), others are more optimistic that Africa can leapfrog into the services economy. (Newfarmer et al., 2019; Nayyar et al., 2021).

In separate literature, there are debates about when and how Africa can eliminate greenhouse gas emissions. On the surface, the discussion has focused on how Africa can transform its economies while maintaining its low level of emissions. However, the analysis tends to prioritize climate mitigation efforts and highlight how decentralized and low-carbon energy technologies can serve as the basis for African countries' energy systems (IRENA et al., 2020; and World Bank Group, 2021). On the other hand, countries across Africa have adopted a development vision that includes a significant manufacturing base.[6] Special Economic Zones (SEZ) or industrial parks have grown significantly over time. There are estimated to be 237 SEZs across 47 African countries currently (UNCTAD, 2021a). There are many different development pathways for Africa, and each has different implications for the climate. The discussion about African development, economic growth, and poverty reduction is tightly tied to the climate discussion, especially regarding structural transformation.

[5] Poverty headcount ratio at $2.15 a day (2017 PPP).

[6] Africa Union (AU) (2015).

Energy system modeling is often used to explore transition pathways toward a decarbonized energy system and assess related economic and climate impacts. In this paper, we analyze the state of literature on energy transition modeling in Africa and assess the extent to which it considers the development agenda. We assess, (i) the evolution of energy transition modeling over time and across the continent, (ii) the extent to which existing literature accounts for the continent's pressing development challenges, (iii) the extent to which all available technologies are considered or restricted in current models, and (iv) how this knowledge generation and intellectual leadership evolves and informs global policy formulation on Africa.

To answer these questions, we extracted and analyzed information from papers published between 2000 and 2021 in peer-reviewed academic journals that include empirical and theoretical analyses regarding energy transition issues. We focused on papers that were scenario-based with energy mix projections and related outcomes such as CO_2 emissions, energy consumption, or development outcomes. The screening retained 156 papers that meet all our inclusion criteria.[7] We extracted detailed information from each paper, including the number of scenarios, the projections horizon, the geographical coverage, the technologies considered or excluded, and whether development is an outcome of interest or not. Additionally, we coded the information about the authors and their affiliations along with some attributes of the journals in which the papers were published.[8] With this data, several findings stood out.

First, the body of knowledge on energy transition modeling on the African continent is growing quickly, but it is largely a new phenomenon. Over 90% of the research in this space was published after the 2015 Paris Agreement, and 60% was published during the three years prior to 2021. In terms of spatial coverage, over one-third of the studies focus on the two largest economies on the continent, Nigeria and South Africa. Nearly half of the countries in Africa are not covered in the research papers examined. The majority of the studies (58%) focus on a single country, whereas 21% of the studies analyze the region as one entity. The top three most covered countries are South Africa, Nigeria, and Ghana. The countries that tend to receive the most attention are larger countries, both in terms of the GDP and/or the population; we did not find a similar relation for GDP per capita or CO_2 emissions per capita.

Second, the vast majority of the papers model the 2030 horizon, followed by the 2050 horizon, both of which are global targets. The 2030 horizon relates to the United Nations' sustainable development goals and the 2050 horizon is often considered a reference point for the global net-zero emissions target.

Very few papers discuss the pathways to desired transition targets and focus instead on the end line or target date for net-zero emissions. No paper systematically discussed how to move from the present state to the desired end line on a year-per-year or decade-by-decade basis.

Additionally, a very limited number of scenarios is considered. Half of the papers have fewer than three scenarios and over 90% of papers have a maximum of six scenarios. Considering the complexity and the multi-dimensionality of the issues at hand, one would expect larger numbers of scenarios that reflect the uncertainties and normative choices that are typically at play in decision-making at the nexus of economic development, energy transition, and emission reduction.

Third, climate goals are the most predominant in the papers reviewed; 90% of papers focused on determining the optimal energy mix and 60% on the emissions pathways for meeting climate goals. Only 10% of the papers included the development dimension as an outcome of interest. For papers that considered development, the projected electricity consumption and economic growth projections were rather modest. The largest per capita electricity consumption projection for sub-Saharan Africa (SSA) in 2050 was pegged at 1,500 kWh, which represents approximately half of the global average in 2017 and is even more insignificant when compared to OECD and U.S. consumption levels (7,992 kWh and 12,573 kWh, respectively). These consumption targets seem to be driven by Africa's historically low economic development and electricity demand dynamics, but it may very well lock the continent in a low-ambition target. Also, the

7 The screening process's details can be found in the methodology section.

8 The full questionnaire used to extract information from the papers can be found in appendix.

minimum target for Tier 2 of the World Bank's Multi-Tier Framework (MTF)[9] that is sometimes used as a consumption target is insufficient to support productive uses and modern living conditions.

Integrating large shares of renewables into the grid comes with significant system costs (IEA, 2011). We explored the extent to which papers considered the extra investments needed to meet the extra systems costs that come with the integration of high shares of renewables in the energy mix. We find that an overwhelming majority of the papers do not consider the cost of the transition. Only 4% of the papers go beyond the cost of the energy technology and to discuss the cost of the energy transition.

Fourth, in terms of technologies considered, we found that despite the push against fossil fuels as a transition fuel in Africa, most of the papers featured them in the transition path projections. Very few papers restricted their technology scenarios for the transition to the rather unrealistic assumption of a renewables-only future (See Wu et al., 2017; Jacobson et al. 2018; and Timmons et al., 2020). Also, among the least studied are technologies such as carbon capture, hydrogen, nuclear energy, or electrofuels, whereas these are key technologies that the IPCC recognizes as playing a key role in reaching global net-zero emissions (IEA, 2021; IPCC, 2022; and IRENA, 2022). Solar, wind, and hydro were by far the most considered technologies across board and were predominant in the long-run energy mix.

Finally, regarding knowledge generation, whereas Global North-Global South collaboration is often encouraged as a means of knowledge exchange, we found that only 12% of the papers represent such collaboration. The overwhelming majority of the papers are exclusively authored by researchers based outside of Africa (63%) whereas 25% of the papers are produced by researchers based on the continent. The fact that the researchers in this space are predominantly based outside of the continent may not be an issue in itself, provided that approaches do not differ significantly between the Africa-based and non-Africa-based researchers. However, we identified some trends which are worth highlighting. First, the publications without Africa-based authors were published in higher-impact factor journals, and the authors had much higher citations. To the extent that these papers influence global policy debates, it implies that Africa's voice in the knowledge space is driven by intellectuals not based on the continent. To assess the policy influence of the papers produced on Africa, we considered the extent to which they were referenced in recent reports by the IPCC (the three working groups of rounds 5 and 6, and the special reports). We found that only 13% of the papers in our sample were cited in the IPCC reports. 75% of the papers cited in the IPCC reports were authored by researchers based outside of Africa.

Contrary to the policy citations, we did not find any meaningful differences in the scientific citation of the paper,[10] the approaches, and the analysis, except for one dimension: non-Africa-based scholars are far more likely to study the continent as one entity, whereas most African-based authors tend to study individual countries. We found no difference regarding the extent to which either group considers development outcomes as the primary outcome of interest in their respective analysis.

This paper contributes to existing knowledge in three ways. First, with the recent explosion of research on energy transitions in Africa, it is important to synthesize this work, identify gaps, and opportunities for future knowledge development. A few recent papers have utilized a systematic review approach, but these papers tend to focus on the technicality of the modeling and enhancing models (Dioha, 2017; Trotter et al., 2017; Emodi et al., 2019; Kang et al., 2020; Musonye et al., 2020; Apfel et al., 2021; and Mutezo and Mulopo, 2021). The closest to this paper is Mulugetta et al. (2022), which examines the alignment of climate goals with the specific development objectives of different African countries in designing their energy transition pathways. However, the paper does not use a systematic review approach and instead relies on country case studies to define a framework. This paper, to the best of our knowledge,

9 The MTF defines access to energy services (including electricity and modern energy cooking) that goes beyond binary metrics and includes multiple dimensions such as adequacy, availability, reliability, quality, affordability, legality, health, and safety. The framework comprises six tiers of access, ranging from Tier 0 (no access) to Tier 5 (full access), and involves different uses. For instance, Tier 2 of household electricity access corresponds to an annual electricity consumption between 73 kWh and 365 kWh for general lighting, phone charging, television, and fan (see Bhatia and Angelou (2015)).

10 The scientific citation of a paper corresponds to how often other scientific papers cite the paper. We used Google Scholar to get the number of paper citations (see Section 3 on the methodology for more details).

is the first to focus on the synthesis of the substantive findings of energy transitions research in Africa and the policy implications. Additionally, given the fast growth of this research area, with over 60% of the papers produced just in the past three years, a regular synthesis can contribute to our understanding of the research direction.

Secondly, very few papers have attempted to integrate energy transition research and global economic transformation issues within the same framework (see for e.g., Kumar et al. (2021)). This paper sheds light on the subject and furthers the conversation around bringing these two tightly related issues within the same framework.

Finally, our paper contributes to the growing literature examining diversity and the representation of voices from the Global South in the knowledge generation space. Recent papers in several fields have shed light on the importance of diversity in the knowledge space (Blom et al., 2015; Porteous, 2020; Zavale and Schneijderberg, 2020; Koffi, 2021; Koffi and Wantchekon, 2022). In the critical space of climate change, which could shape societies' futures for centuries, this paper is – to our knowledge – the first attempt to assess an aspect of intellectual diversity in the space of energy transition modeling for Africa. Furthermore, the paper adds to that literature by highlighting not only the extent of diversity or representation in the literature, but also considers how that diversity might or might not matter.

The rest of the paper is organized as follows:
In Section 2, we present the contextual background. Section 3 is devoted to the methodology, leaving out non-essential details in the appendix. Section 4 presents and discusses the results. In Section 5, we conclude with policy recommendations.

SECTION 2

Contextual Background

Africa faces different challenges, including low levels of economic development, high poverty rates, inadequate industrialization, weak energy systems, vulnerability to climate change, and more. While there have been some recent improvements in macroeconomic indicators with real GDP growth estimated at 6.9% in 2021, compared to 1.6% in 2020 (AfDB, 2022), these improvements may not be durable given the persistence of COVID-related drawbacks, the current war in Ukraine, and other uncertainties in the global economy. Africa has the lowest GDP per capita of any continent in the world, and projections estimate that global poverty will soon become a primarily African phenomenon with 90% of the world's poor living in Africa in 2030 (Beegle and Christiaensen, 2019; Calderon et al., 2019). Significant effort is required to close the large historical economic development gap. The real per capita GDP growth must reach substantial and sustained levels to overcome persistent poverty on the continent.

Africa also suffers from a lack of human capital, including highly skilled workforce and infrastructure; this hinders development efforts. Sub-Saharan Africa (SSA) has the lowest level of human capital (World Bank, 2020) and stands at the bottom of all developing regions in all dimensions of infrastructure performance (World Bank, 2017). This negatively affects the labor market through the reduction of labor productivity and reduces the capacity of the poor to find income-earning opportunities. The low unemployment rate in Africa does not reflect the reality of the labor market in the continent, given that only a small fraction of the African labor force is employed in formal jobs, and nearly nine out of ten workers engage in the informal sector, mostly in subsistence agriculture and self-employment (ILO, 2019).

The persistent slow economic performance of Africa is also associated with a low rate of industrialization, which makes the continent the least industrialized region in the world (Abreha et al., 2021). The dominance of the service sector in a region with no industrial base is a departure from historical development trends observed in developed countries. More industrialization is needed to achieve a level of structural transformation that is sufficiently robust to induce sustained economic growth and job creation. A modern and adequate energy system is a prerequisite for such structural transformation and creates the foundation for complementarities with important factors including investment, labor, and technological progress. Most African countries lack adequate and equitable energy systems that are commensurate with their ambitions of achieving sustained economic growth. Electricity supply, demand and access are not sufficient in Africa, putting the region behind all other regions in the world (Kojima and Trimble, 2016; Blimpo and Cosgrove-Davies, 2019).

An important set of questions arise around the intersection of energy and economic growth. First, is energy a limiting factor for economic development in the African context? Second, how can the continent better capitalize on its large energy resources endowment to drive economic growth? Several studies investigate those questions, and some of them argue that energy is a limiting factor for economic growth (Allen, 2009; Ayres and Warr, 2009 and Malanima, 2020). Malanima (2020) refers to *Liebig's law of the minimum*[11] to support the notion that a deficit in energy can compromise economic progress and future development. Moreover, using historical data, Allen (2009) and Ayres and Warr (2009) find that availability of cheap energy, and not technological progress as often hypothesized, has been the main driver of the past economic growth in other geographies. Putting this in the African context, it is paradoxical that African countries' abundantly endowed energy resources have not yet been sufficiently exploited to power economic progress.

According to UNEP (2017), Africa has relatively important reserves of non-renewable energy sources, namely, oil, gas, and coal – representing 7.6%, 7.5%, and 3.6% respectively of the world's total. The continent is also endowed with large hydropower potential accounting for roughly 12% of the global total. It also has abundant renewable energy potential with solar irradiation ranging from 5 to 7 kWh/m^2 all year round, relatively strong wind power potential, and large amounts of land suitable for biofuel production. However, this energy potential has not been adequately exploited to drive development on the continent. On the contrary, electricity costs in Africa are higher than in any other region in the world due to many factors, including poor management and planning (Streatfeild, 2018). Governments frequently provide energy subsidies to make electricity affordable, mainly for poor households. Furthermore, electricity is not reliable, negatively affecting 80% of firms between 2008 and 2018, with an average of six hours of disruptions leading to losses that are estimated at about 8% of annual sales; a significant total compared to just one hour per month of disruptions in OECD countries (World Bank, 2018). This situation partially explains the prevalence of energy poverty in Africa.

Given the important role of electricity in powering different sectors of the economy and improving human living standards, it becomes obvious that Africa needs to exploit more of its energy potential to achieve its ambitious goals of economic development and poverty eradication. However, African countries should adopt long-term planning for their energy transition that balances reliance on cheap energy resources with the imperative of addressing climate change.

The context of climate change in Africa is unique. The continent has a low contribution to global greenhouse gas emissions, both historically and currently, but is highly vulnerable to environmental catastrophes resulting from climate change. Africa has contributed less than 3% of current global energy-related carbon dioxide (CO_2),[12] and has the lowest emissions per capita in the world (IEA, 2022). SSA's contribution is even smaller; excluding South Africa, the entire region accounts for only 1% of global emissions. Nevertheless, with a high exposure to climate change and low adaptive capacity, Africa is one of the most vulnerable continents (Boko et al.,2007 and Niang et al., 2014). Average annual economic losses from climate change are currently estimated at 5–15% of GDP per capita growth between 1986–2015, and are projected to be much worse in the future, reaching 16–64% by 2030 under the high warming scenario (AfDB, 2022). With such a high risk of economic losses and given that climate mitigation efforts are not likely to be sufficient to avoid environmental catastrophes, countries should prioritize investment in adaptation (Pindyck, 2022). Thus, Africa must consider a large deployment of adaptation options to improve its resilience to climate change and invest more in resilient infrastructure.

There is growing interest in climate adaptation, as expressed in Nationally Determined Contributions (NDCs) emerging from Africa. The adoption rate of adaptation policy or planning by countries in Africa has reached 72% (UNEP, 2021). Unfortunately, the

[11] *Liebig's law of the minimum is initially developed in agricultural science. It reflects how the scarcest essential nutrient can limit the growth of a plant even though other essential nutrients are abundant.*

[12] This is even smaller (i.e., 2.07%) if we consider the cumulative CO_2 emissions from 1960 to 2018.

mobilization of required funding to implement these adaptation plans is slow. The Global Center on Adaptation (2021) has estimated that $331 billion of investment will be needed to implement adaptation strategies in 40 African countries by 2030. These countries have committed to support 20% on average from their national budget and are seeking the remaining 80% from donors. However, the adaptation-related financial transfers to the continent between 2014 and 2018 were below U.S. $5.5 billion per year; this was half of mitigation-related financial support (Savvidou et al., 2021). Given the lack of concrete commitments from international donors to fund adaptation measures in Africa, governments in the region must rely on domestic funding to implement their adaptation strategies; sustained economic growth is needed to make this possible. Given this context, economic development cannot be neglected in any of the short-, medium- or long-term international climate commitments of African countries.

Climate imperatives should be balanced with ambitious development objectives when African countries are planning their energy transition. Rich economies are better positioned to implement climate adaptation measures than poorer countries are (Smit and Pilifosova, 2003). The better developed a country is, the more resources it can invest in resilient infrastructure and low-carbon energy solutions. Moreover, adopting a system-wide approach that factors in development and the cost of the energy transition will position African economies to effectively integrate intermittent renewable energies at a large scale and invest in a wide range of clean firm power sources that can balance that variability on the path toward eventual net-zero emissions.

Consequently, the extent to which economic development is given consideration can be used to assess whether a specific energy transition model is relevant for the context of African countries.

SECTION 3

Methodology

We conducted a systematic review to evaluate the state of energy transition modeling research on Africa. A systematic review is a research method that systematically assesses existing primary research to provide an up-to-date summary of the state of research knowledge on a specific topic (Higgins et al., 2019). The structure of the methodology follows the "Preferred Reporting Items for Systematic review and Meta-Analysis" (PRISMA) protocols that include five stages: (1) inclusion criteria, (2) literature search, (3) data screening and selection of studies, (4) data extraction, and (5) data analysis (see Figure 1).

3.1 Inclusion Criteria

Given that the review focuses on research knowledge, we included only peer-reviewed papers. For consistency, we excluded grey literature (i.e., academic working papers, reports from government, private sector, or institutions, etc.). We also limited our selection to papers written in English and published from 2000 to 2021.[13]

As a first step, we developed a set of criteria in line with energy transition modeling on Africa. We identified three key inclusion criteria. The first is the geographical scope of the paper. We included papers that focus on Africa as a region, African subregions, or individual African countries. The geographic inclusion criterion was extended to include papers with a global scope and specific results on Africa, African subregions, or African countries. The second was a thematic criterion; here we focused on them that align with the notion of the energy transition. In addition to the term "energy transition," this inclusion criteria included the following themes: decarbonization, low-carbon transition, energy pathways, low-carbon pathways, and net-zero emissions. We excluded studies that focused solely on sustainability issues. Sustainability goes beyond the topic of energy and includes other environmental concerns like waste management, biodiversity, circular economy, recycling, and more. The third inclusion criterion concerned methods. Given the focus on energy transition modeling, we included empirical papers that are model-based or

13 Other relevant official languages on the continent are French, Portuguese, Arabic, and Spanish, covering 31 countries. However, researchers in these countries more often than not, write in English.

scenario-based studies and had energy mix (i.e., share of given energy technologies) scenarios or paths. Therefore, we excluded reviews, background, and theoretical studies.

3.2 Literature Search

We used the inclusion criteria described above to search for relevant papers that were included in the review. For exhaustivity, we used the following major electronic databases: Scopus, Web of Science (WOS), EBSCO, and JSTOR. The search resulted in a total of 2,993 papers distributed as follows: 1,716 papers in Scopus, 1,103 papers in JSTOR, 124 papers in EBSCO, and 50 papers in WOS. In addition to searching these four major databases, we extended our selection to include papers from review papers and references. This ensured that we covered all relevant papers that were in line with our selection criteria as much as possible. This additional round of search produced 19 papers, with 15 papers from review papers and 4 papers from citations. We then uploaded 3,012 papers to Covidence, a web-based software platform that provides tools for primary screening and data extraction.

3.3 Paper Screening and Selection

Given the likelihood that some papers appear in multiple search engines, we first screened the total of 3,012 papers for duplicates in Covidence. This initial screening identified 147 duplicates that we excluded from the analysis. We then screened the remaining 2,865 papers by title, abstract, and keywords, following the inclusion and exclusion criteria. We then read each of the papers and assessed whether the study satisfied all the three dimensions of inclusion criteria. At this stage, we excluded many papers (2,573) mainly because the papers did not focus on energy transition modeling. The second round of screening for full text involved 292 papers. Using the same inclusion criteria once again, we fully read each paper and excluded 136 papers, mainly because they were descriptive papers rather than model-based or scenario-based papers and they lacked an energy mix focus. Note that different reviewers undertook the screening process, and there were discussions to reach a consensus in case of disagreement. Overall, the screening process left 156 papers that constituted the final sample used in the analysis.

3.4 Data Extraction

From the 156 papers, we used Covidence to extract key information that covered different variables used in the analysis. We started the data extraction by developing a data extraction template in Covidence (see Appendix for more details). Five groups of information were coded in the template: (i) authorship and geographical coverage, (ii) main scope of the paper, (iii) methodology and data, (iv) results, and (v) key challenging questions.

The first set of information included affiliations and names of the first five authors listed on the paper and a list of African countries or subregions covered in the paper. It also highlighted whether this coverage was exclusive or extended to other regions or countries in the paper. The second set concerned information on whether energy, economic development, and emissions pathways were discussed in the paper. It also included how different economic, sociological, and political aspects were addressed in the paper. Thus, a classification that differentiates techno-economic systems, socio-technical systems, and systems of political actions was provided. In the third group, we provided information on various approaches, methodologies, and levels of data disaggregation (from national to firms and households). Papers also differed with regards to the richness of the results and related discussions. Thus, the fourth set was devoted to whether the paper had short-, medium- or long-term projections, the number of scenarios, and whether the scenario paths were detailed and fully discussed. Finally, since several factors can affect the results of energy transition modeling we accounted for those factors in a fifth group. This included, for example, how restrictive the energy technologies considered in the paper were, how the energy cost for each energy technology was calculated and discussed in the paper and whether the total cost factored in the entire energy transition cost.

We then used the template to extract all the relevant information in Covidence. Two different reviewers were involved in the data extraction process and worked independently on all the selected papers. The reviewers met regularly to address any potential inconsistencies and clarification questions related to the coding and adjusted the template accordingly. After the two reviewers had completed the extraction, the team met to validate the extracted data. Whenever there was a divergence between the information provided by the reviewers, a consensus was required. The team then discussed and solved the inconsistencies. After the team had validated the data extraction, the final data was extracted from Covidence and combined with the general information on the paper, including title, abstract, name of the journal, year of publication, etc.

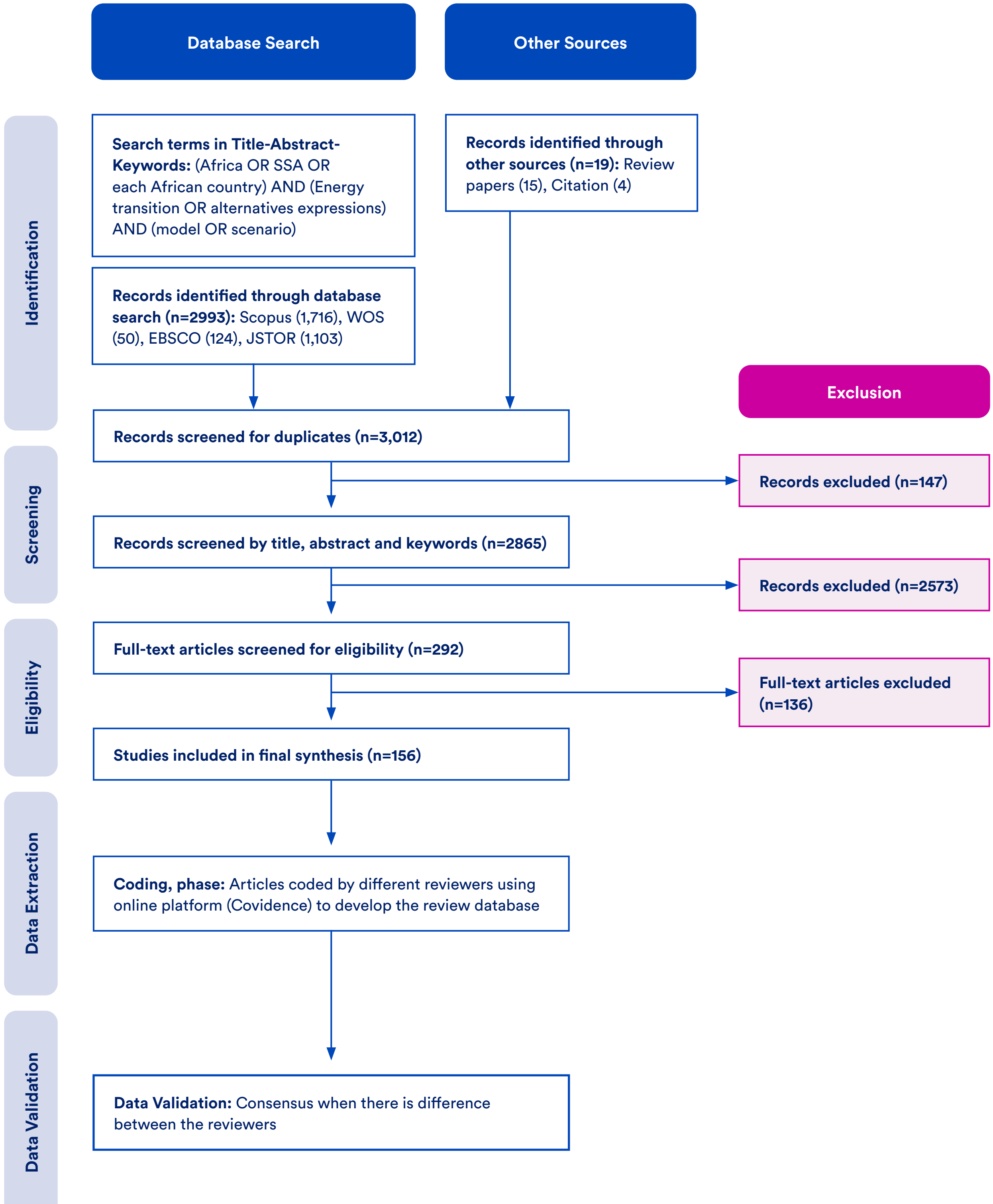
To investigate the restrictions on the geographical coverage of our sample of papers, we collected additional data on the socio-demographic and economic characteristics of African countries such as GDP, population, official language, tourist arrivals, and the electricity consumption and CO_2 emissions. This data was obtained from the World Bank's WDI database.

3.5 Data Analysis

Given the scope of the review, additional information was needed to assess and record the scientific reputation of the authors and the impact of their papers in advancing research on energy transition and policy decisions (see Appendix for more details). To assess how African-based institutions are involved in advancing research on energy transitions on the continent, we classified the author's affiliation and highlighted whether the institution is based in or outside of Africa. We also differentiated across academic, public, non-profit, regional, or international institutions. This classification used the information provided in the final data from Covidence, which was refined using the google search engine.

We discussed four levels of reputation: (i) The author, (ii) the paper, (iii) the author's affiliation, and (iv) the journal. First, we provided the number of citations for each of the authors listed in the paper. This was performed with the academic search engine Google Scholar. Second, we used both scientific and policy citations of the paper. For the scientific citation, we used Google Scholar to get the number of paper citations. Given the international recognition of the climate change community for IPCC reports, we referred to policy citations as papers cited in the reports released by the IPCC. We considered recent IPCC reports, namely rounds 5 and 6 (all three working groups) and the special reports. Third, we documented the rank of the author's institution using the SCImago ranking. Note that the SCImago Institutions Rankings (SIR) is a classification of academic and research-related institutions which is based on research performance, innovation outputs, and societal impact. Given the research focus of our review, we primarily used the research rank that covered the following aspects: publications in terms of number and quality, international collaboration, scientific leadership in terms of number and excellence, open access, scientific talent pool, etc. Fourth, we provided the journal's impact factor as provided on the journal website. The impact factor is developed by Clarivate and used as a standard proxy to assess the reputation of an academic journal. It is an index that reflects the yearly mean number of citations of publications in the last two years in the journal.

Figure 1: Paper Identification, Screening, and Data Coding Process



SECTION 4

Results and Discussion

4.1 Overview of Papers' Key Attributes

A summary of the characteristics of the papers analyzed in this study is outlined in Table 1.
An overwhelming majority of the models focus on techno-economic systems, without much consideration of the socio-political constraints that matter for policy implementation. For example, a transition from the use of biomass to liquefied petroleum gas (LPG) may be financially and technically feasible but households' habits and preferences may dampen either the adoption of the new technology or the phasing out of the previous one, leading to what is already often observed as fuel stacking (See Masera et al. (2000); Muller and Yan (2018); Ochieng and al. (2020); and Perros et al. (2022)). Similarly, phasing out fossil fuels for renewable energy is likely to face major internal political constraints. For instance, the powerful leaders from the oil sectors in oil-producing countries have significant political power to influence policies and delay the transition. Also, energy subsidy reforms are an extremely political and sensitive concern that often face complex implementation challenges with civil protests motivated by the fuel price increase. In our sample of papers, we found that only a handful of papers (3%) had dealt with those social considerations, but none addressed the political constraints. Neglecting social and political considerations in energy transition models, especially in the African context where cultural perceptions, beliefs, preferences, and political actions play an important role in social decision-making, may limit the possibility of implementing a transition pathway even if this is technically and economically feasible.

The papers that met the inclusion criteria spanned both bottom-up and top-down approaches to energy transition modeling. Both approaches have advantages and drawbacks. Bottom-up models account for details of the technologies, whereas the top-down approach accounts for the macroeconomic relationship to the energy sector. Over two-thirds of the papers took a bottom-up approach, and another quarter took a top-down approach. The wide use of the bottom-up approach in modeling African energy transition allows a deeper exploration of several energy technologies. However, this is constrained by the intensive data requirements (both quality and quantity) in a region with significant data access limitations. Some papers (7%) utilized both approaches by using a hybrid approach despite the added modeling complexity. These papers complemented the bottom-up supply side approach

Table 1: Overview of Key Model Characteristics

		Frequency (%)	N	Examples
Model Classification	Techno-economic systems Socio-technical systems Political actions systems Other	95.51 3.21 0 1.28	149 5 0 2	 448, 880, 1003, 1112, 1156 624, 198
Model Approach	Top-down Bottom-up Both	24.32 68.92 6.76	36 102 10	65, 123, 167, 596, 609, 631 1003, 1112, 196, 214, 334 1480, 557, 40, 266, 285, 430, 1077
Number of scenarios	0-3 4-6 7-23 24+	49 40 8.9 2.2	66 54 12 3	
Furthest horizon	Before 2030 2030 Between 2030 and 2050 2050 Beyond 2050	8.00 38.40 17.60 28.80 7.20	10 48 22 36 9	285, 430, 802, 1216, 1303, 1480 123, 161, 196, 266, 1383 65, 318, 514, 525, 893 107, 238, 334, 529, 580 1409, 1314, 1003, 253, 1572
Discusses transition path	No Yes	63.82 36.18	97 55	

Notes: This table presents key selected characteristics of the papers. Column 3 shows the frequency, Column 4 is the equivalent number of papers and Column 5 gives the identification number of selected examples of papers (see Appendix for the full list).

with the top-down demand side approach.[14] In line with the dominant use of the bottom-up approach, we found that the majority of papers (51%) used optimization as a methodology.[15] This shows that most of the papers on the African energy transition provide optimal transition paths that are commensurate with cost-efficient energy solutions. However, because of the data limitations in Africa, researchers often approximate or extrapolate analysis based on developed countries, leading to large degrees of uncertainty in the input data. In turn, it means it is critical to put those optimal paths within the African context when interpreting them and to not rely on the model outputs as factual results.

The modeled time horizon is another key attribute that differentiates the papers included in the study. A large number of the papers (46%) modeled the transition using a 2030 horizon, likely driven by global targets related to the sustainable development goals.[16] The second most prevalent target year was 2050, which is also a global target for achieving net-zero emissions.[17] The review shows that fewer than one paper in ten has scenarios

14 The iterative process of exchanging information on energy price and quantity between the two approaches leads to energy market equilibrium. There are two possibilities of linking the two models: hard-linking approach with a completely integrated and highly complex optimization model, and soft-linking approach with separate models and manual integration.

15 Note that 22% and 12% of papers use the simulation and econometrics methods, respectively, while there is a growing interest of using a combination of methods (6%) and machine learning (1%).

16 The Sustainable Development Goals (SDGs) are a universal call to action to end poverty, protect the planet, and ensure that by 2030 all people enjoy peace and prosperity. SDGs were adopted by the United Nations in 2015.

17 Net zero aims to cutting greenhouse gas emissions to as close to zero as possible, while any remaining emissions are removed from the atmosphere, by oceans and forests.

beyond 2050. The scenarios beyond 2050 are particularly important for Africa as the African Union's Agenda 2063[18] is the defining baseline horizon for the continent's development objectives – most of which are tightly linked to the evolution of energy systems across the continent. Yet, only about 5% of the papers model a horizon beyond 2063. Thus, global targets determine the time horizon of the scenarios that are explored in most of the papers on energy transition modeling in Africa.

Additionally, we reviewed whether the papers systematically discussed the pathways to an eventual energy transition or only focused on some key intermediate and endline results. We found that nearly two-thirds of the papers discussed findings focusing solely on the end line usually 2030 or 2050. No attention was given to the pathways themselves and the interim years. The papers that had discussed pathways restricted their focus to key intermediate years. For example, papers that modeled the 2050 horizon would occasionally discuss 2030. No paper consistently and systematically discussed the pathways on a year-per-year basis or in an interval of years, such as a five-year basis. The lack of focus of the intermediate results along the pathways can make it difficult to implement those models in the African context, where large investments in the energy sector are needed and should be balanced with other development priorities like education and health.

Finally, we documented the total number of scenarios presented in each paper. The number of scenarios is important because most modeling assumptions carry uncertainties that could stem from the data quality to unexpected short-term shocks that could derail from the most likely transition path at the time of the modeling. This is particularly important in the African context where detailed data may not always be readily available. One way to address this challenge is to present a large range of scenarios or classes of scenarios (see Trutnevyte (2016), Price and Keppo (2017), Rozenberg and Fay (2019), and Morris et al. (2022). However, as reported in Table 1, half of the papers report just three scenarios or fewer. Furthermore, over 90% of the papers report six or fewer scenarios. Three papers stood out as outliers reporting respectively 99 and 3660 scenarios.

For instance, Orthofer et al. (2019) use a multi-scenario analysis to explore uncertainties connected to shale gas exploitation in South Africa. The authors reported 3,660 scenarios based on shale gas extraction cost and carbon price. Bamisile et al. (2020) and Bamisile et al. (2021) have explored 99 different scenarios based on energy technologies combination in the context of Nigeria. Thus, the review shows that most of the papers report a small number of scenarios. Even though this is a common problem in the energy modeling space worldwide, fewer scenarios for the advanced economies can be justified to some extent because they have better data covering longer periods of time. Those economies are also more stable with less variance in growth. However, this is especially problematic for African countries, which are poorer and more volatile (see IMF(2022b)).

4.2 Energy Transition Modeling Over Time and Space Across the Continent

In this section, we discuss the spatial and intertemporal distribution of research on energy transition modeling across Africa. The continent is generally under-researched when it comes to several important issues and the body of knowledge may be thin at critical times for policy choices, especially at the global level. We found this to be the case when it comes to energy transition research. For instance, our initial sample included 3,012 papers (with 1,716 on Scopus) that focused on Africa, while our search query on Scopus applied without restrictions to Africa, yielded a sample of 15,470 papers; this means an 11% coverage for Africa.[19]

Even though Africa is under-researched, Figure 2 shows that energy transition modeling is a recent but fast-growing phenomenon in the continent. The 2015 Paris Agreement marked a critical step in climate action among nations. Yet, at the time of this agreement, less than 10% of the papers retained in this study were available (See Figure 3). This means that Africa entered the Paris Agreement with a limited knowledge base to inform its standing. There has been a steady and steep growth in the number of papers published on Africa since the Paris Agreement. Figure 3 demonstrates that

[18] Agenda 2063 is the shared strategic framework of Africa for inclusive growth and sustainable development. The framework takes account of past achievements, challenges, and opportunities at the national, continental, and global levels to provide the basis and context in which the continent's transformation is being designed and implemented (AU, 2015). Agenda 2063 was adopted in 2015 by the African Union.

[19] At the global level, Candemir et al. (2021) and Elsevier (2021) have found over 1.6 million papers between 2001–2020 that focus on clean energy research related to net zero. Note that their search query goes beyond the specific themes like "net zero", "decarbonization", "carbon neutral" or "zero carbon" and includes SDG 7 on Affordable and Clean Energy and SDG 13 on Climate Action.

the last three years of our sample (2019-2021) recorded 60% of the papers, representing 150% more than the previous 18 years combined. The new research can be a rich source of guidance to inform Africa's stance and approach to climate action going forward.

The geographical coverage of the region is equally important. Each of the 54 countries on the continent has unique attributes in terms of land size, population, institutions, or economic prospects. Modeling Africa as a unit not only may masks these differences but may also be impractical in terms of policy implementation. Recommendations for the continent may not necessarily be aligned with those that may emanate from a careful analysis of any single country on the continent. On the other hand, most countries in the region lack scale for individual modeling to bear meaningful significance. We report the geographical coverage in Table 2 and depict it in Figure 4 and Figure 5. We found that 58% of the papers focused on an individual country and 21% modeled the entire region. The rest focused on a group of African countries (9%) or included the region or countries within the region in analysis that looked beyond the region (13%). The predominant focus on individual countries highlights the importance that researchers attribute to countries' differences. However, there are large disparities in how individual countries are considered in the papers. For instance, of all the studies covering individual countries, over one-third of them focus on the two largest economies in the region, South Africa (18%) and Nigeria (17%). Ghana is a distant third with 8% of the studies. Half of the countries were not covered by any studies. Twelve countries were covered by single studies respectively.

The general pattern shows a strong correlation between the size of economies and the number of studies.[20] Similarly, the population size correlates highly with the number of studies conducted on a country.[21] We also explored the correlation between individual country coverage and three other proxies for the size of the country in per capita terms: GDP, electricity consumption, and CO_2 emissions. For the GDP per capita, we found a positive but smaller correlation. Only four countries were

Figure 2: Yearly Number of Publications

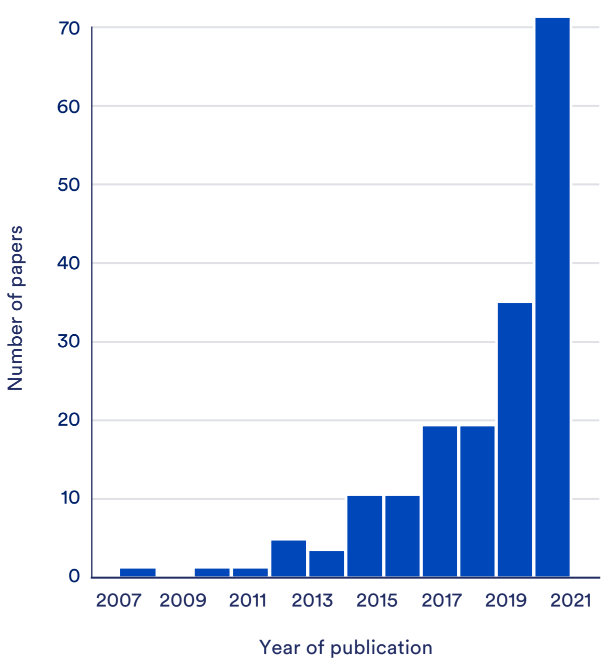
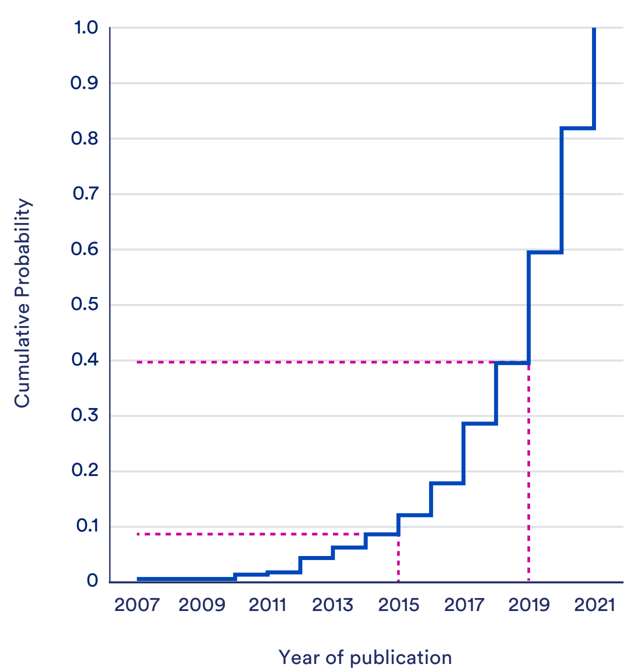


Figure 3: Cumulative Number of Publications Over Time



20 The equation of the fitted line gives share of papers=0.81*percentage of African GDP+0.34 with R^2=0.67.

21 The equation of the fitted line gives share of papers=0.95*percentage of African Population+0.09 with R^2=0.5. Note that the pattern remains after removing Nigeria and South Africa.

Figure 4: Geographical Distribution of Country Studies (Number)

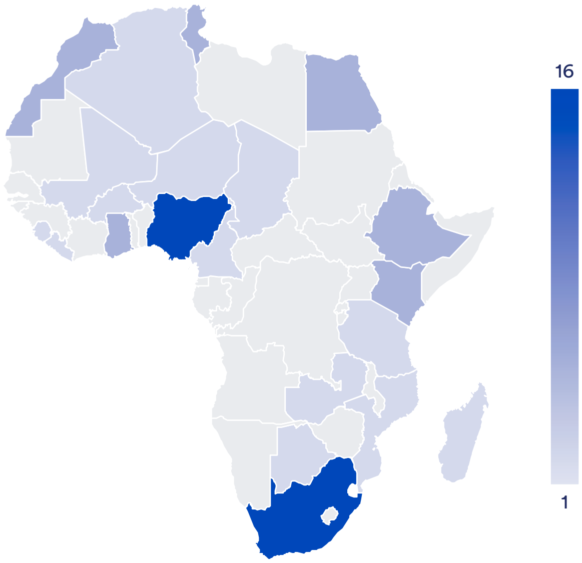


Figure 5: Geographical Distribution of Individual or Group of Country Studies (Series)

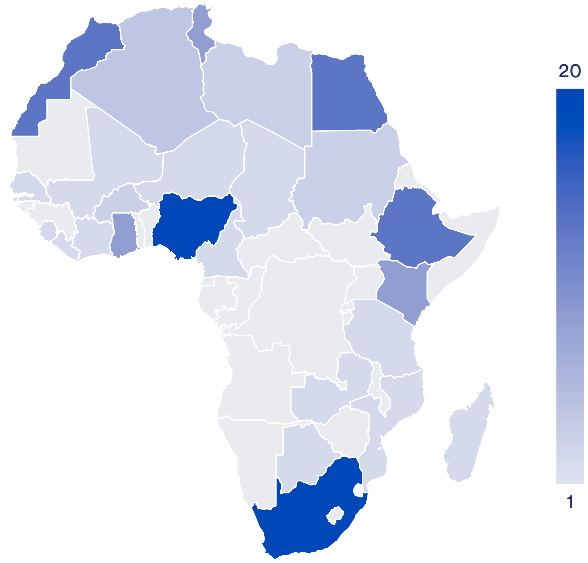


Table 2: Intertemporal and Geographical Distribution of Energy Transition Research in Africa

		Frequency	Number
Geographical coverage	Africa Region exclusively Includes Africa Region Multiple African countries exclusively One African country only Includes selected African countries	20,51 4,49 8,97 57,69 8,33	32 7 14 90 13
Most covered countries	Top 1: South Africa Top 2: Nigeria Top 3: Ghana	17,78 16,67 7,78	16 15 7
Least covered countries	Countries with only one study: Algeria, Botswana, Burkina Faso, Cameroon, Chad, Gambia, Liberia, Madagascar, Mali, Niger, Sierra Leone, Zambia	13,33	12
Countries not covered in standalone studies	Angola, Benin, Burundi, Central African Republic, Comoros, Djibouti, Côte d'Ivoire, Equatorial Guinea, Eritrea, Gabon, Guinea, Guinea-Bissau, Lesotho, Libya, Malawi, Mauritania, Namibia, Republic of the Congo, São Tomé and Príncipe, Senegal, Seychelles, Somalia, Sudan, Swaziland/Eswatini, Togo, Uganda, Zimbabwe.		27

covered among the top ten countries with the highest GDP per capita. The countries not covered but with large per capita GDPs were Seychelles, Equatorial Guinea, Gabon, Namibia, Libya, and Djibouti. Also, the five most covered countries rank 6th, 19th, 16th, 22nd, 32nd, respectively in terms of GDP per capita. Given our focus on energy transition, we also used per capita electricity consumption as a proxy for the size of the country. We found similar patterns as GDP per capita. Only six of the ten countries with the highest per capita electricity consumption were covered. We found a positive relation between CO_2 emissions per capita and the likelihood that a country is studied. Of the top 19 countries with the highest CO_2 emissions per capita, only South Africa emerged in the list of the five most covered countries, namely, South Africa, Nigeria, Ghana, Kenya, and Ethiopia. We also found that those correlations were significant (see Appendix 7.1).

4.3 Economic Development and Energy Transition Modeling

Table 3 describes how energy, climate goals and economic development objectives are addressed in the papers. Energy transition is inextricably linked to economic performance through energy cost, availability, and reliability. For most economies in Africa, the energy transition will present both challenges and opportunities for development prospects. Yet, for the full sample of papers we analyzed, only about 10% of them considered economic growth and poverty metrics as outcomes of interest. Most studies (90%) were concerned with the energy mix, and in nearly 60% of the papers, emissions was one of the variables of interest. It is arguably desirable that in the context of Africa, where development outcomes are of critical interest, the nexus of the energy mix, emissions, and development outcomes be considered simultaneously. However, only 7% of the papers considered these issues together. Furthermore, we found similar patterns when we considered a subsample of papers that exclusively focused on the entire continent or individual country. Thus, energy and climate goals are prioritized over development objectives.

We also reviewed the assumptions that are used in the papers and found that while development outcomes are not often considered as outcomes of interest, they are nevertheless discussed in a greater number of papers (40%). Those papers discussed the development implications of their models in terms of economic growth, job creation, poverty, etc. However, the economic assumptions were often not clearly stated, making it challenging to assess the extent to which those models reflect the development ambition or realities of the country or the continent.

Electricity consumption projection may be one proxy for how ambitious the economic development assumptions used in a paper are. Table 3 also synthesizes the per capita electricity consumption resulting from scenarios for all the papers that provided that information. We restricted our sample to papers that focused on the entire region or subregion and then compared the electricity consumption targets to the average electricity consumption at the global level and across the regions. We found that the highest target for SSA in 2050 is only 1,500 kWh, corresponding to the current consumption levels of countries like Colombia, Cuba, Egypt, Moldova, Tajikistan, and below the average of middle-income country average of 2,037 kWh. This consumption level, the highest envisioned, represents less than half of the current global average of 3,152 kWh in 2017 (See OECD and IEA (2019)), one fifth of the OECD average and one tenth of the U.S.'s average. Within Africa, there are also some disparities as scenarios on Northern Africa reflect more ambitious electricity consumption targets (2,143 kWh per capita). Thus, we conclude that the scenarios on energy transition for SSA do not consider ambitious targets on per capita electricity consumption.

The choice of electricity consumption targets seems to be driven by the data sources that are usually used to project the electricity demand. First, most of the scenarios use historical data and socio-economic and demographic projections to derive the implications for future electricity consumption. Given the fact that SSA has historically had a low level of economic development and electricity demand, the continent is likely to be locked in a low ambition target. Second, some scenarios use the minimum targets of the Multi-Tier Framework (MTF) developed by the World Bank (see Bhatia and Angelou (2015)). Those scenarios usually consider the minimum requirement for Tier 2, which corresponds to an annual electricity consumption of 73 kWh for a household that uses only low-load power such as lights, a television, or a fan for four hours per day. This target is extremely insufficient to support productive uses and a modern standard of living. Third, some papers project that future electricity consumption of SSA will mimic the current levels of consumption in Northern Africa. For instance, Bazilian et al. (2012) projects that the electricity consumption level of SSA (excluding South Africa) by the year 2030 will reach that of the Northern Africa in 2008 (i.e., 1285 kWh per capita).

Table 3: Development Objectives in Energy Transition Models for Africa

		Full Sample		Africa Region Exclusively		One African Country Only	
		Percent	Number	Percent	Number	Percent	Number
Outcome of interest	Development (growth, poverty) Emissions Energy mix pathway Energy-Emissions-Development	10,14 59,46 89,86 6,76	15 88 133 10	10,34 44,83 82,76 6,25	3 13 24 2	11,36 63,64 89,77 8,89	10 56 79 8
Discusses development implications		39,74	62				
Discusses cost of transition		3,85	6				
Electricity consumption (KWh) per capital	Minimum for SSA in 2030 Minimum for Africa in 2030 Maximum for SSA in 2050 Maximum for Africa in 2050 Northern Africa Eastern Africa (2030) Western Africa (2050)		100 599 1500 1888 2143 1187 858-948				

Note: For the electricity consumption (KWh) per capita, the subsample only includes papers that focus on the entire Africa or subregions.

Moreover, Calvin et al. (2016) shows that all scenarios in SSA project an electricity use per capita in 2050 that is below the level of Northern Africa in 2012. We did not come across any paper in our sample that explored the implications of SSA reaching OECD or global levels of electricity consumption per capita.

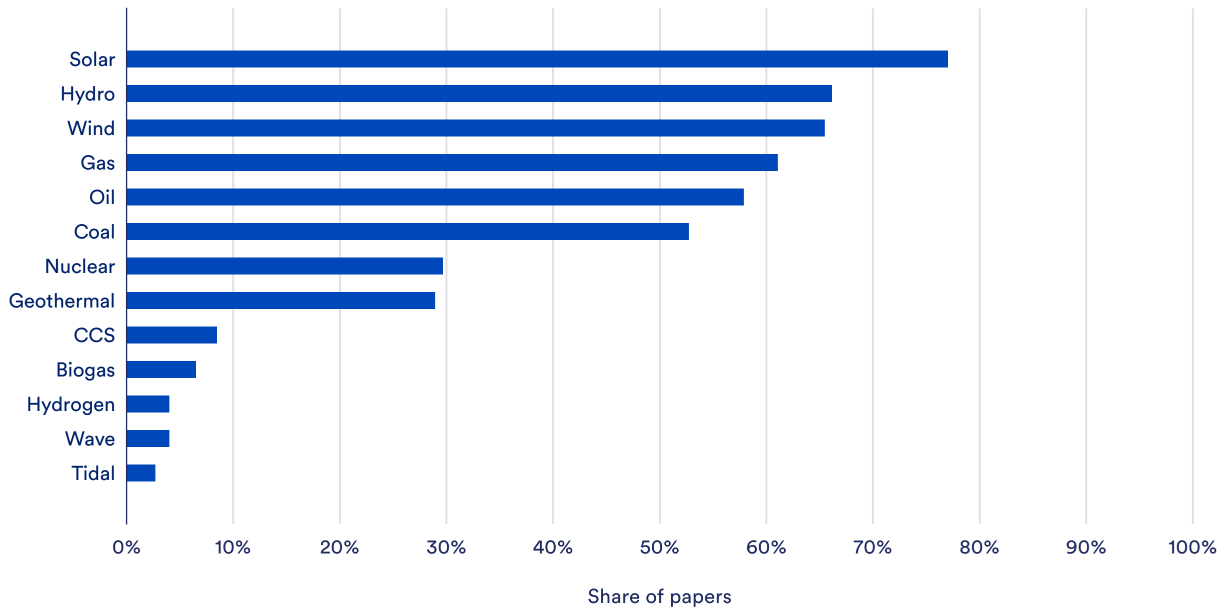
In addition to the electricity consumption targets, we also assessed the economic targets stated in the papers. In general, we found that most of the papers did not transparently report the economic assumptions that informed their scenarios. In papers where GDP growth targets were provided, we found that those targets were below the 7% target of the AU Agenda 2063. These low economic targets do not reflect the projected population growth in Africa and the economic ambition of the continent as expressed in the AU Agenda 2063.

The total cost of the energy transition goes beyond the cost of building power generation technologies alone, as typically captured in models. It includes the extra investments needed to upgrade existing power infrastructure or to build new modern infrastructure. Achieving high shares of renewables in the energy mix requires electricity systems that can balance variable renewable sources with firm power. We explored how these additional costs were factored into existing analysis and found that a majority of the papers did not consider the cost of the transition. Only 4% of the papers went beyond the cost of the energy technology to discuss the comprehensive system cost of the energy transition.

4.4 Technology Options in Modeling Energy Transition in Africa

Different policy reports, including those from the IRENA (2022), IEA (2022), and Skea et al. (2022), have identified key energy technologies that are expected to play vital roles in the low-carbon transition. Those technologies include wind, solar, biomass, hydro, geothermal, nuclear, hydrogen and fossil fuel sources equipped with carbon capture and storage (CCS). In this section, we discuss the extent to which studies focusing on energy transitions in Africa take these various technology options into account. For the most ignored energy technologies, we analyzed the geographical distribution and compared it with the potential of the country to develop those specific energy technologies. Figure 6 displays the share of papers that consider each of the energy technologies. This distribution shows that CCS, hydrogen, and some firm low-carbon energy

Figure 6: Distribution of Energy Technologies Considered in the Scenarios



Note: (i) Hydro: Among papers that consider hydro, 45% do not specify the types of Hydro, while 55% differentiate the hydro energy technologies (with 46%, 39%, 19% and 2% consider small hydro, large hydro, pumped hydro and hydro import, respectively). (ii) CCS: any of the papers does not consider carbon utilization.

technologies (i.e., Nuclear, geothermal, and biogas) are the least considered technologies in transition modeling for Africa. Less than 30% of the papers we reviewed considered these technologies. Renewable energy sources like wind, solar, and hydro are the most considered energy technologies. In addition, over 1 in 10 papers restricted the technology options to only renewable energy.

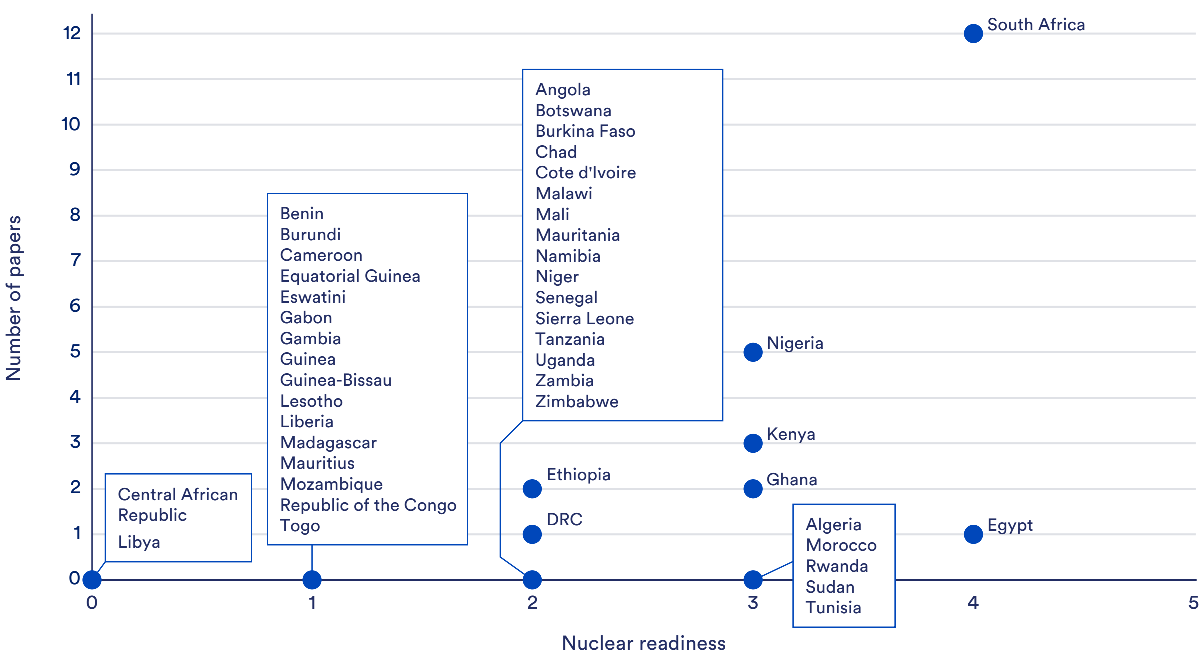
In general, scenarios in research that focus on mitigation policies and targets tend to support the complete phaseout of fossil fuels use and favor renewable and clean energy sources. To some extent, there was also consideration of fossil fuels (gas, for instance) equipped with CCS, at least for a transition period. However, it remains challenging to replace the conventional firm energy sources with only variable and intermittent sources. Geothermal energy and hydro technology are good candidates to provide a firm source to back up variable renewable energy but are limited to country-specific resource availability. Nuclear energy, with a potentially high development of both small modular and advanced reactors, is another firm low-carbon energy source that can be deployed together with renewable energy. Despite the general push against fossil in dominant energy transition debates, our review shows that most papers (between 53% and 61%) that focus on energy transition modeling in Africa feature fossil fuels (oil, gas, and coal) in the transition pathway. However, we find that despite the important role nuclear energy is expected to play in the low-carbon transition, it is the least considered technology among the conventional firm energy sources, with only three in ten papers considering that option.

The restriction of nuclear in energy technology considerations may be a result of its limited deployment in Africa currently. Only one African country (South Africa) among the thirty-two countries assessed had an operating nuclear reactor. On the one hand, Figure 7 shows that nuclear technology is currently being considered in countries with larger economies (including Nigeria, Kenya, Ghana, Ethiopia). On the other hand, Figure 7 also shows that some African countries may be ready to deploy advanced nuclear technology by 2030 (for example, Mozambique, Morocco, Algeria, Sudan, and Rwanda). Meanwhile, studies on those individual African countries do not consider nuclear energy technology. Thus, the papers focusing on individual African countries do not fully account for their nuclear potential and may miss the opportunity to address the implications of including advanced nuclear in the energy mix of those countries.

On the renewables side, Figure 6 shows that solar and wind, are the most predominant carbon-free technologies (65% and 77%) considered in the papers, while wave and tidal energies are the least covered (3% -4%). As firm energy sources, hydro is included more often than geothermal (more than twice as often). Only 29% of papers consider geothermal energy technology, and these mostly focus on Kenya and Ethiopia. But the East Africa Rift has one of the highest geothermal energy potentials in the world, covering countries like Kenya, Ethiopia, Tanzania, Uganda and Rwanda. Also, the other regions (Algeria in Northern Africa) have significant potential for geothermal energy (see Elbarbary et al. (2022)). However, only Kenya and Ethiopia have existing installed geothermal power plants, which are operational only in Kenya (IRENA, 2020a). This may explain why papers that considered geothermal technology only focused on these two countries.

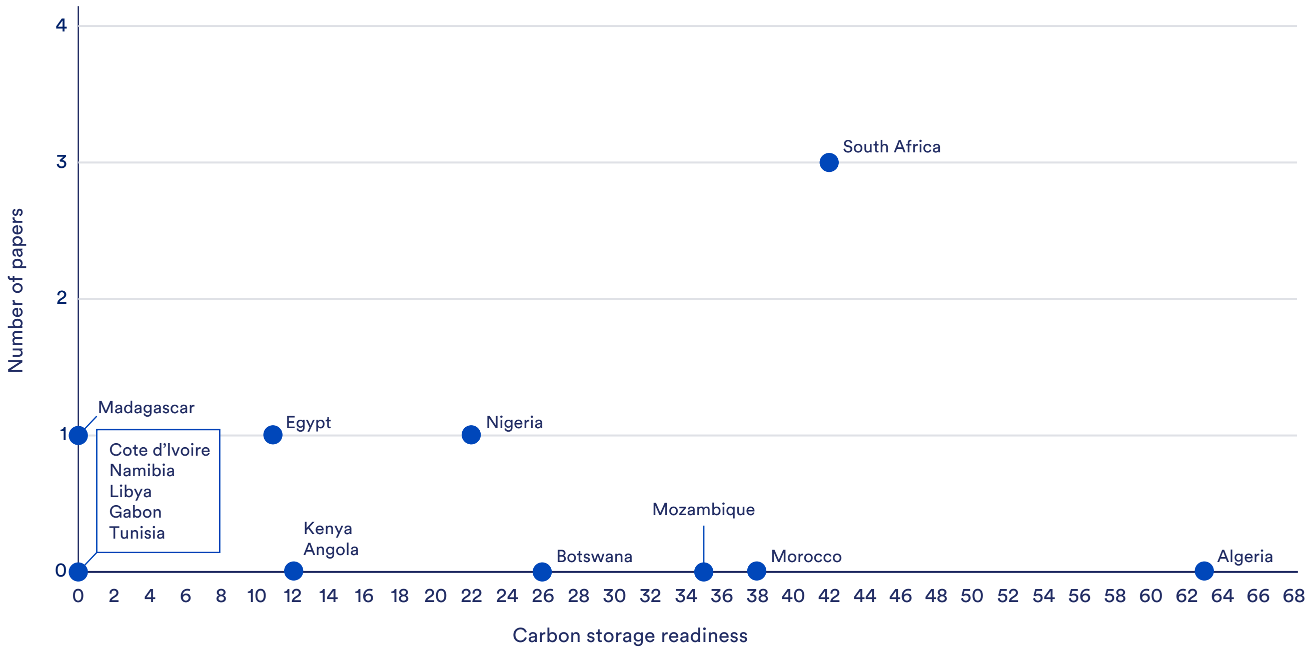
Marine energy technologies (wave and tidal) were the least considered renewable energy technologies, with just a single paper focusing on tidal energy in Ghana. Even though some African countries have the potential to use marine energy (see AfDB (2021)), the large deployment of this technology is still constrained by the relatively high upfront costs, lack of adequate infrastructure, large investments requirement, and technology immaturity and performance (Skea et al., 2022). According to IRENA (2020b), wave energy is abundant and predictable, and has a global theoretical potential that is large enough to meet all global energy demand. A number of countries including the United Kingdom, Canada, Australia, China, and Denmark have deployed advanced marine projects at the demonstration

Figure 7: Nuclear Technology Consideration Versus Potential



Notes: We use the nuclear readiness provided in Lovering et al. (2021) that covers the country's relative preparedness and motivation for developing advanced nuclear power and includes internal institutions and controls such as policy and regulatory agencies, as well as external signals of interest such as engagement with supplier countries and international institutions like the International Atomic Energy Agency. Note that this readiness index does not include the electricity demand projection. The legend is the following: (4) Ready by 2030, (3) Potentially ready by 2030, likely ready by 2050, (2) Not ready by 2030, potentially by 2050, (1) Not ready 2030, Unlikely ready by 2050, (0) Conflict zone or internationally sanctioned. The countries in each box share similar attributes in terms of nuclear readiness and the number of papers.

Figure 8: Distribution of Papers by CCS Technology Inclusion and Carbon Storage Potential



Notes: The Carbon storage readiness is based on Consoli (2018). "0" for the score means "not reviewed". The countries in each box share similar attributes in terms of carbon storage readiness and the number of papers.

and small commercial stages (IEA, 2021). However, there is a need to implement adequate policies to support innovation for the deployment of marine energy technologies globally, and specifically in African countries.

We also analyzed carbon capture and hydrogen technologies, even though the two technologies are not currently deployed at scale (Bouckaert et al., 2021). Further innovation is needed to commercialize these technologies and deploy them at scale. Figure 8 describes the carbon storage readiness in Africa and the distribution of carbon capture and storage consideration across individual African countries. The figure confirms that the continent is not ready yet to implement carbon capture technologies at a large scale.[22] Our review also shows that a minimal number of papers considered hydrogen (4%) and carbon capture (8%) technologies. Hydrogen is only explored in Nigeria and Chad in standalone country studies, while carbon capture technology is explored in standalone country studies on South Africa, Nigeria, Egypt, and Madagascar- mainly higher-polluting countries. Nevertheless, some African countries like Algeria, Morocco, and Mozambique have prospective potential in carbon storage as shown in Figure 8, and warrant further research.

4.5 Research and Intellectual Leadership on Energy Transition in Africa

In this section, we discuss intellectual leadership and some important drivers of research on energy transition modeling in Africa. First, we describe the status of the research with some selected indicators on the authorship that give a general overview of the papers reviewed.

22 Consoli (2018) refers to a large-scale deployment for a carbon storage project that has an annual injection rate of a million tonnes or greater. Most of the twelve leading nations in carbon storage are OECD countries, except China, Brazil, United Arab Emirates, and Saudi Arabia.

Second, we assessed who and what drives intellectual leadership and whether this matters or not. We analyzed the papers' authors and research focus in relation to intellectual leadership in the space.

4.5.1 State of Energy Transition Research on Africa

Table 4 shows an overview of energy transition research authorship with summary statistics on papers and authors. The first group of indicators are specific to the authors and includes the number of authors involved in the paper, the author's citations (namely, the average and most cited co-author) and the rank of the author's affiliation (i.e., average, and most ranked co-author's affiliation). On average, three researchers are involved in a paper, which also corresponds to the median, confirming the low dispersion of the number of authors (i.e., standard variation of 1). On the contrary, the distribution of the author's citations is highly dispersed and skewed to the right. The median of the author's citation (1305) and the most cited authors (2427) are much lower than their average (2795 and 6034, respectively), showing a high standard deviation of 4549 and 11438, respectively. This illustrates the fact that authors with low citations are more frequent than authors that are highly cited. Moreover, the rank of the author's affiliation had a similar distribution with a high dispersion and skewed to the right.

The second group of indicators relate to characteristics of the paper itself, namely the impact factor of the journal in which the paper was published and two indicators of paper citations: the annual scientific citation and the policy citation (citation in IPCC reports). The papers that we reviewed were published in journals that had an average impact factor of 7, which is close to the median of 6 and to the impact factor of some field journals like climate change, climate policy, ecological economics, and energy policy. This indicates that energy transition modeling in Africa has attracted field journals with high impact factors. Furthermore, on average, the papers have been annually cited eight times compared to the median of five annual citations. This shows that papers with high annual citation are less frequent in the sample. In addition to scientific citations, we also explored policy citations by searching the papers in our sample that were cited in IPCC reports. We found that only 13% of the papers in our sample were cited in IPCC reports.

4.5.2 Drivers and Relevance of Intellectual Leadership

In this section, we discuss the characteristics of the researchers involved in energy transition modeling in Africa. We examine the geographical affiliation of authors who are driving intellectual leadership and explore whether the general overview described in Section 4.5.1 changes in any way. We then analyze

Table 4: Paper and Authors' Summary Statistics

	Average	Percentile 10%	Percentile 50%	Percentile 90%
Number of authors	3 (1)	2	3	5
Author's citations	2795 (4549)	176	1305	5697
Citations of the most cited Author	6034 (11438)	248	2427	11375
Rank of the Author's affiliation	30 (25)	4	24	72
Rank of the most ranked Author's affiliation	24 (24)	1	15	60
Journal impact factor	7.05 (7.48)	2.33	6.14	9.75
Annual paper's citations	8.46 (9.07)	1	5.42	20.5
Percentage of papers cited in IPCC reports	13% (34%)	–	–	–

Note: Numbers in "( )" are standard deviation.

the focus of the papers with respect to who drives intellectual leadership, the degree of influence associated with the papers and whether or not the category of researchers leading the production of knowledge matters.

4.5.2.1 Authors' Profile and Institutions

The first characteristic of interest is the geographical affiliation of the researchers involved in the papers. We consider three categories of researchers: papers written by (i) only Africa-based authors, (ii) only non-Africa-based authors, or (iii) collaboration between Africa-based and non-Africa based authors. The distribution of papers in Table 8 shows that 63% of the papers do not have an Africa-based author. For the remaining 37% of papers that include at least one Africa-based researcher, 25% are authored only by Africa-based researchers and 12% are collaborative efforts between Africa-based and non-Africa-based researchers. This is an indication that energy transition research on Africa is dominated by researchers based outside of the continent.

The notion of North-South partnerships to promote research and knowledge transfer to Africa does not appear to be at play here prominent given the small number of papers that were published through such collaboration. This discrepancy in knowledge generation on energy transition in Africa is in line with the general gap that exists in research capacity between SSA and the rest of the world, as the research output on the continent is less than 1% of that of the world (Blom et al., 2015). One of the key drivers of this gap is inadequate funding for research and development (R&D) in SSA. In fact, SSA is the second region that has the lowest R&D expenditure after the Central Asia, both in terms of the share of global R&D expenditure (i.e., 0.7%) and the percentage of GDP (i.e., 0.38%) (UNESCO, 2020). Therefore, policy actions that encourage better allocation of resources to R&D will be important to reduce this gap, limit the phenomenon known as "brain drain" and make it more attractive for African researchers to center their research agenda on the main challenges in Africa, including energy transition modeling.

For the remainder of this section, we discuss whether the profile of the researchers and the potential influence of their papers vary depending on their geographic affiliations (see Table 8). On average, papers by Africa-based authors have one author fewer than papers by non-Africa-based authors. For the papers that involve collaboration, only one Africa-based researcher collaborates with three non-Africa-based researchers on average. We also found that on average, papers without Africa-based researchers were cited 286% times more than papers published by only Africa-based researchers. The cumulative distribution of each category of researchers confirms the dominance of non-Africa-based researchers at all levels of author citations. This is even more pronounced when considering the most cited authors, with a difference of as much as four times. Thus, top non-Africa-based researchers are less likely to co-author papers with Africa-based researchers. The result is similar if we consider the rank of the author's affiliation given that Africa-based institutions are generally lower ranked.

Regarding the influence of the paper, we find a much more moderate difference. On average, papers with no Africa-based authors are published in higher-ranked journals less than twice as often as papers with only Africa-based authors are. Even though papers with Africa-based authors are less likely to be published in highly ranked journals and involve top researchers, we found that the difference in the annual citation of the paper is rather modest. This indicates that the interest of the scientific community in those papers goes beyond the profile of the researchers that publish the papers. However, we note that the most annually cited paper (i.e., 53 citations) is a paper that involves only Africa-based authors.

Contrary to the scientific citations, we find that policy citation (i.e., references cited in IPCC reports) is disproportionately dominated by papers produced by researchers based outside of Africa.

Table 8 also shows that three out of four papers cited in IPCC reports are published by only non-Africa-based researchers. Papers with only Africa-based researchers and those published in collaboration with Africa-based researchers account for only 10% and 15% respectively. Thus, considering policy influence, the share of papers on Africa involving an Africa-based researcher and cited in IPCC reports represents only 3% of all papers produced on Africa (compared to about 10% for papers not involving any Africa-based author). The fact that Africa-based researchers are less cited and less known in both the international policy and scientific circles may explain why their intellectual contributions are under-represented in international policy reports. Also, note that papers with high policy influence have higher international exposure, thus higher (i) annual citations and (ii) journal impact factor where the paper is published, and (iii) citations of the most cited author.

Figure 9: Geographical Coverage by Authors' Location

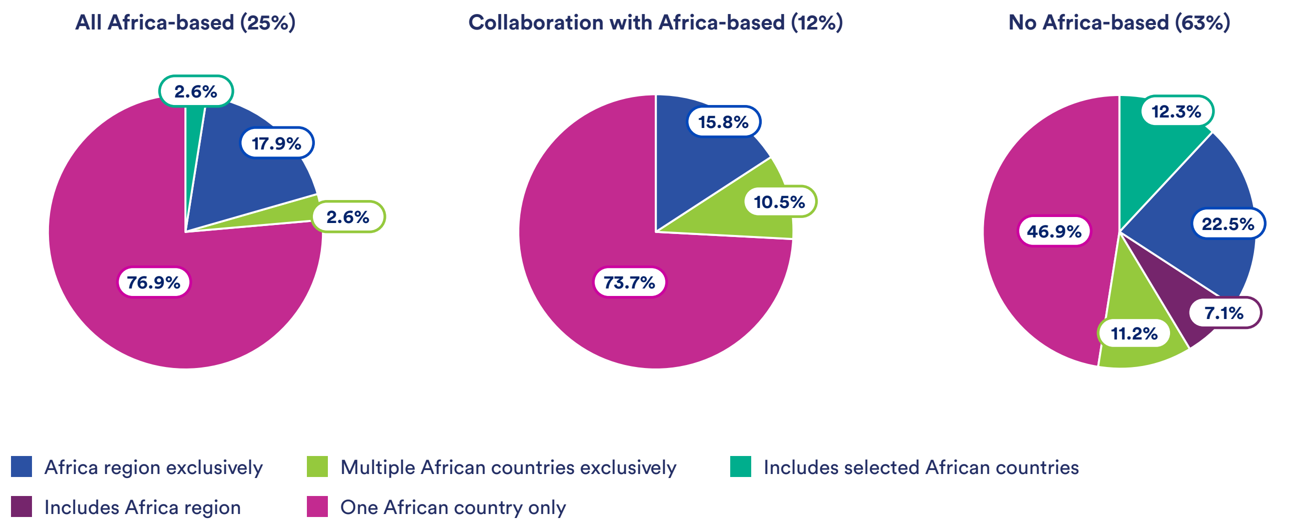


Table 5: Distribution of Papers by the Geographical Focus

Share of Papers	Multiple African Countries Exclusively	One African Country Only	Includes Selected African Countries	Africa Region Exclusively	Includes Africa Region
Author' Information					
Average Author's citations	2025	2032	5037	3428	7199
Average citations of the most cited author	3957	4235	12186	7895	13741
Average rank of the Author's affiliation	26	33	26	27	16
Average rank of the most ranked Author's affiliation	36	41	27	32	17
Paper's Information					
Average journal impact factor	11	6	7	9	6
Average of annual paper's citations	6	6	12	13	16

Note: Numbers in "( )" are standard deviation. Number in "[ ]" is the average number of Africa-based authors that collaborate with non-Africa-based authors. The sample of IPCC reports includes round 5, round 6 and all special reports.

We also investigated the extent to which intellectual leadership influences the recent growing interest in energy transition modeling on Africa. In general, the non-Africa-based researchers publish more papers than Africa-based researchers per year (see Figure 11 in the appendix 7.2).

4.5.2.2 Differences and Similarities by Authors' Geographical Location

The previous section provides evidence that researchers based outside of Africa dominate energy transition modeling research on Africa. Does this matter? We investigated whether a category of researchers tend to focus more on specific countries or regions than the others. We also explored the implications for the profile of the authors and the influence of their papers given the geographic coverage. We further considered other key dimensions that we have discussed in previous sections of this report, such as economic development considerations, numbers and horizon of the scenarios, energy technologies restrictions, etc.

Types of Papers by Authors' Geographical Location

Figure 9 describes the geographical focus of the papers within each category of the author's geographical affiliation. It shows that papers with Africa-based authors mostly focus on individual African countries. Africa-based researchers are 30 percentage point more likely to work on country-specific research than non-Africa-based researchers are. We also found that despite the limited collaboration with Africa-based researchers, collaboration is absent for studies that consider Africa in a global context. Furthermore, we assessed the proportion of papers with no-Africa-based authors for each type of geographical focus. For individual country focus, this proportion was only 51%, while it was 69% when the focus was on the entire continent exclusively and 100% when it went beyond the continent. This highlights the fact that papers with no Africa-based authors tend to cover the entire continent as one unit. The fact that Africa-based researchers are more knowledgeable of the context in individual African countries may explain why their contribution is more frequent for standalone country studies. The implication is that some important country-specific characteristics and challenges related to the implementation of energy transition policies are less likely to be addressed in studies with no Africa-based researchers. This creates a potential bias in cases where those papers involve highly influential researchers and have a high scientific and policy influence.

To confirm this, we further analyzed the profile of authors and the influence of their papers depending on their geographical focus. We found that more cited researchers and those from better ranked institutions have a tendency to work less on papers that focus on individual African countries (see Table 5). Regarding scientific influence, papers that went beyond individual African countries were more frequently cited (at least twice) than papers that focused on individual countries (See Table 5). However, the results for the impact factor of the journal where the paper is published are contrasted. Table 5 shows that papers that focus on individual countries or on Africa as a region were published in journals with equivalent impact factors. On the other hand papers that focus exclusively on the whole continent or multiple African countries were published in journals with much higher impact factors.

Overall, our results show that it matters how papers consider regions and countries when research in energy transition modeling on Africa is dominated by researchers who are based outside of the continent.

Development, Scenarios, and Technology Restrictions by Authors' Attributes

In addition to the geographical coverage, we investigated additional dimensions that the intellectual leadership outside Africa may potentially influence. Regarding scenarios, we analyzed the farthest time horizon considered in the paper, the consideration of intermediate results along the transition path, and the average number of scenarios (see Table 8). The results show that in general, there are few post-2050 scenarios regardless of the authors' geographical affiliation. Nevertheless, papers with only Africa-based authors are more oriented to Sustainable Development Goals (SDG) (i.e., 2030) while papers with no-Africa-based authors focus more on net-zero emissions targets (i.e., 2050). Moreover, papers published through cross-regional collaboration are more likely to consider the specific AU agenda of 2063 (13%) than papers with only Africa-based researchers (3%) or no Africa-based author (6%). We also found that discussion of the transition path is less frequent in papers with only Africa-based researchers (24%) than papers that do not involve Africa-based authors (42%). However, we did not find any difference in the number of scenarios included in the papers.

Table 8 also highlights two different aspects of development consideration in the papers: the objectives of the papers and their implications. The results show that the authors' attributes do not correlate with the

Table 8: Distribution of Papers by the Geographical Affiliation of the Authors

Share of Papers	Full Sample	All Authors are Africa-Based	Collaboration with Africa-Based Author	No Africa-Based Author
General Trends				
Percentage	100%	25%	12%	63%
Number of papers	156	39	19	98
Average number of authors	3 (1)	2 (1)	4 [1] (1)	3 (1)
Author' Information				
Average Author's citations	2795 (4549)	1247 (1709)	1743 (1824)	3592 (5410)
Average citations of the most cited Author	6034 (11438)	1997 (2282)	3963 (4372)	7979 (13808)
Average rank of the Author's affiliation	30 (25)	47 (26)	38 (19)	22 (22)
Average rank of the most ranked Author's affiliation	24 (24)	39 (28)	19 (15)	19 (22)
Paper's Information				
Average journal impact factor	7.05 (7.48)	5.55 (3.41)	4.93 (3.11)	8.03 (8.93)
Average of annual paper's citations	8.46 (9.07)	8.17 (10.40)	8.23 (7.51)	8.62 (8.87)
Citation in IPCC reports	13%	10%	15%	75%
Furthest Horizon				
Up to 2030	46.40%	61%	47%	41%
2031 – 2050	46.2%	35%	40%	52%
2051 – 2063	1%	0	0	1%
Beyond 2063	6%	3%	13%	6%
Number of Scenarios and Discussion of the Transition Path				
Yes	36%	24%	29%	42%
Average number of scenarios	3.91 (2.92)	3.83 (2.95)	4.13 (1.77)	3.90 (3.08)
Considerations of Pathways				
Energy	90%	86%	83%	93%
Emissions	59%	57%	67%	59%
Development	10%	9%	6%	12%
Energy-emissions	58%	57%	67%	57%
Energy-emissions-development	7%	6%	6%	7%
Discussion of Development Implications				
Yes	39.74%	41.03%	42.11%	38.78%
Energy Technologies Considerations				
Solar	77%	69%	89%	78%
Hydro	66%	64%	58%	68%
Wind	65%	54%	74%	68%
Gas	61%	54%	47%	66%
Oil	58%	49%	42%	64%
Coal	53%	54%	37%	55%
Nuclear	29%	21%	26%	34%
Geothermal	29%	15%	11%	38%
CCS	8%	3%	0%	12%
Biogas	6%	3%	5%	8%
Hydrogen	4%	0%	16%	3%
Wave	4%	3%	5%	4%
Tidal	3%	3%	0%	3%

Note: Numbers in "( )" are standard deviation. Number in "[ ]" is the average number of Africa-based authors that collaborate with non-Africa-based authors. The sample of IPCC reports includes round 5, round 6 and all special reports.

frequency of papers analyzing development outcomes. We also found similar results for energy technologies, except for energy technologies that are less frequently considered (see Table 8). Papers with no-Africa-based researchers consider key energy technologies like nuclear, geothermal, CCS and hydrogen more frequently, than papers with only Africa-based authors.

Citations and Policy Influence

Energy transition issues are key concerns in the global discussion on climate change. Several considerations, including climate geopolitics and scientific evidence, can potentially influence those international climate discussions and related decisions. Therefore, in the context of energy transition modeling on Africa, it is important to analyze the characteristics of papers and researchers that have a potential to influence both the scientific community and policymakers. For the authors' profiles, we selected the most cited authors in our sample with citations higher than 10,000. We considered the top 10 most cited papers and citations in IPCC reports as indicators of the potential high influence of the papers.

Table 9 shows that all the fifteen most cited authors are not based in Africa and only one of them has published a paper in collaboration with Africa-based researchers. We also found that none of them has contributed to a paper that considers development as an outcome of interest. Nevertheless, we did not find significant differences when it came to the geographical focus or the horizon of the scenarios. Nearly half of those papers focus on individual African countries (Mostly Kenya and Nigeria) and the considerations of transition towards SDGs and net-zero emissions targets are quite equivalent.

With respect to the papers' influence, Table 7 emphasizes some differences in terms of the geographical affiliation of the authors involved in the most cited papers. 55% of the papers were written with no-Africa-based authors while 45% of the papers included at least one Africa-based researcher (including 9% for collaboration). We also found that those papers are similarly oriented toward 2030 and 2050 targets and only one paper considers economic development objectives. However, those papers tend to focus more on the continent as a unit than on individual African countries (representing only 18% against almost 50% for Africa exclusively).

Table 6: Characteristics of Papers in the Final Sample by IPCC Citation Status

		Cited	Not Cited
Annual number of citations		14 (10)	8 (9)
Average of journal impact factor		10.04 (12.93)	6.62 (6.32)
Average citations of the most cited author		10447 (18467)	5370 (9908)
Furthest horizon	Up to 2030 2031 – 2050 2051 – 2063 Beyond 2063	30% 55% 5% 10%	49% 45% 0% 6%
Geographical coverage	Africa Region exclusively Includes Africa Region Multiple African countries exclusively One African country only Includes selected African countries	40% 15% 10% 30% 5%	18% 3% 9% 62% 9%
Consideration of development objective		15%	9%
Discussion of pathways		60%	33%
Top 10 most cited paper		27%	73%
Most cited Authors		33%	66%

Note: Standard deviations in parentheses.

On policy influence, Table 6 shows that most of the papers cited in IPCC reports focus on 2050 targets while the consideration of 2030 and 2050 targets are equally prominent in papers not cited in IPCC reports. The focus on individual African countries is more frequent (i.e., 62%) in papers not cited in IPCC reports than papers cited (i.e., 30%). Moreover, higher proportions of papers cited in IPCC reports consider economic development and discussion of the transition path than papers not cited. Also note that paper's citation in IPCC reports does not translate into papers' scientific citation and citation of researchers involved in the paper. We found that those papers include fewer top researchers and highly cited papers than the latter.

Overall, we found that the influence of the authors and their papers (both scientific and policy) matters for the development consideration in the paper. Author citation is linked to the geographical affiliation of the authors while the paper citations matter for the geographical focus of the papers. Moreover, citations in IPCC reports are linked with the time horizon of the scenarios in the papers.

Table 7: Distribution of the Top 10 Annually Most Cited Papers

Rank of Citations	Number of Annual Citations	Geographical Affiliation of Authors	Geographical Coverage	Furthest Horizon	Development as Outcome of Interest
1st	53	In	Africa Region exclusively	–	No
2nd	48	Out	**Includes Africa Region**	2050	No
3rd	43	Out	**Includes Ethiopia**	2050	No
4th	37	Out	Africa Region exclusively	2030	No
5th	30	Out	**Includes Benin, Angola, Democratic Republic of Congo, Ethiopia, Niger, Cameroon, Mozambique, Republic of Congo, Botswana, Cote d'Ivoire, Senegal, Tanzania, Ghana, Togo, Zimbabwe, Gabon, Kenya, Mauritius, Nigeria, Namibia, Sudan, South Africa, Zambia**	–	–
6th	29	In	Algeria	2030	No
6th ex	29	Both	Africa Region exclusively	2030	No
8th	27	Out	**Includes Africa Region**	2052	Yes
9th	26	Out	Africa Region exclusively	2030	No
10th	24	In	Africa Region exclusively	2040	No
10th ex	24	In	Tunisia	2030	No

Notes: "in" = Only Africa-based Authors; "out" = No Africa-based Authors; "both" = Collaboration with Africa-based Authors.

Table 9: Distribution of the Most Cited Authors

Rank of Citations	Number of Citations	Number of Papers	Africa-Based Author	Collaboration with Africa-Based Authors	Geographical Coverage	Furthest Horizon	Development as Outcome of Interest
1st	93878	1	No	No	Includes South Africa	2030	No
2nd	79900	1	No	No	Africa Region exclusively	2050	No
3rd	35984	2	No	No	Includes Africa Region	2050	No
4th	27340	2	No	No	Kenya	2035	No
5th	22878	2	No	No	Egypt	2050	No
6th	22624	1	No	No	Kenya	2020	No
7th	20150	1	No	No	Sierra Leone	–	No
8th	19414	1	No	No	Includes Africa Region	2050	No
9th	18439	1	No	No	Africa Region exclusively	2100	No
10th	17607	1	No	No	Nigeria	2030	No
11th	15742	1	No	**Yes**	Africa Region exclusively	2030	No
12th	13283	1	No	No	Kenya	2020	No
13th	11902	1	No	No	Africa Region exclusively	2030	No
14th	11375	9	No	No	Including Ethiopia	2050	No
15th	10130	1	No	No	Nigeria	2040	No

Note: The most cited Authors with citations higher than 10,000. We report the geographical coverage of the most annually cited paper when multiple papers.

SECTION 5

Conclusion and Recommendations

The rapid growth of energy transition modeling in Africa is a welcome development for two reasons. First, it is vital to inform policy decisions regarding the continent's position on climate action on the global stage. It is also essential to help develop experience and capacity in research and policy formulation in this space across the continent. This review sheds light on the patterns emerging from the literature, some of which can inform future research or guide policy in the short and medium term. Energy transition research must be supported and expanded on the continent as nearly half of the countries on the continent lack any study that can inform policy. Additionally, even for countries covered by studies in our sample, there is a dearth of knowledge at the country level. This can impede a comprehensive approach to thinking about the countries' climate actions.

At the granular level, more flexibility and a more comprehensive range of scenarios are often needed to account for the complexities and diversity of the assumptions necessary to obtain a more comprehensive picture of the options available. In addition, more focus on pathways and less emphasis on endpoints would most likely create more useful information for policy formulation and government action. There is also the need to consider scenarios with much higher energy consumption targets for the continent.

We also found that intellectual leadership is disproportionately skewed toward scholars that are based outside of Africa, which is likely reflective of resource commitments and the source of research funding. Consequently, African governments and international donors should commit to supporting local researchers and developing local capacity to inform and further enrich this space going forward.

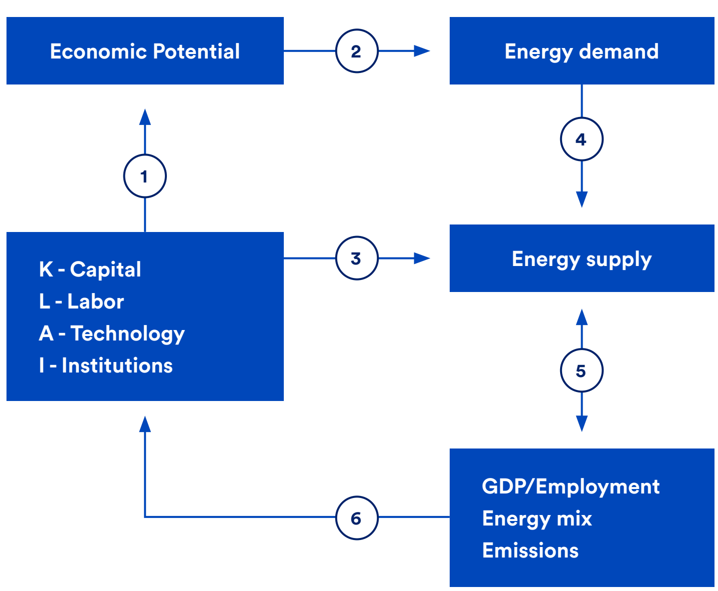
For effective long term policy formulation, the energy transition modeling space must be considered in terms of programs rather than projects. The individual papers provide helpful information as a snapshot, but meaningful, long-term, and sustained climate action also requires long-term and sustained research that adjusts to changing conditions over time. Such options can be achieved more effectively with local institutions, by establishing new entities or by reinforcing the existing ones.

Finally, regarding the central objective of the paper to investigate the nexus between energy, climate, and development, much is left to be done in the literature. Energy transitions research has to a large extent neglected considerations of development imperatives. A framework to integrate these two considerations in a meaningful way is needed but may pose some complexity and difficulties in modeling exercises. Some of that complexity could be lessened by treating energy as a necessary but insufficient input for economic growth. Consequently, we need to consider the extent to which energy is a binding constraint to economic growth, to inform the buildup of energy systems in the short and medium terms, especially when financial resources are scarce. Figure 10 provides a basic illustration of such a possible framework.

Bringing development considerations into energy transition efforts can ensure that energy does not become a binding constraint to development. In the chart, (1) reflects that the fundamentals of the country determine its economic potential. The economic potential can be determined by the highest economic outcomes achieved by a country with similar fundamentals. In (2), economic potential is in turn used to determine the energy demand to be inputted in the model (thus giving a buffer that makes energy unlikely to become a binding constraint to growth). In (3), the fundamentals of the economy also determine the energy supply potential – considerations of some power trade can be included here. In (4), energy demand may exceed supply, but this is unlikely given the determination of the supply potential. In (5), the outcomes from the model include economic growth, emissions, and the energy mix. Some outputs may influence the energy supply, for instance the introduction of a carbon price or new emissions reduction targets. In (6), as the economy grows, it feeds back into stronger fundamentals (greater access to capital, higher skills, better capacity to adopt more advanced technologies, including in the energy sector, etc.).

For poorer countries, climate is a development issue and development is a climate issue. The dual challenge of economic development and climate change calls for more multidisciplinary, collaborative research to address the two issues within the same framework.

Figure 10: Possible Framework of Energy Transition in SSA



SECTION 6

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SECTION 7

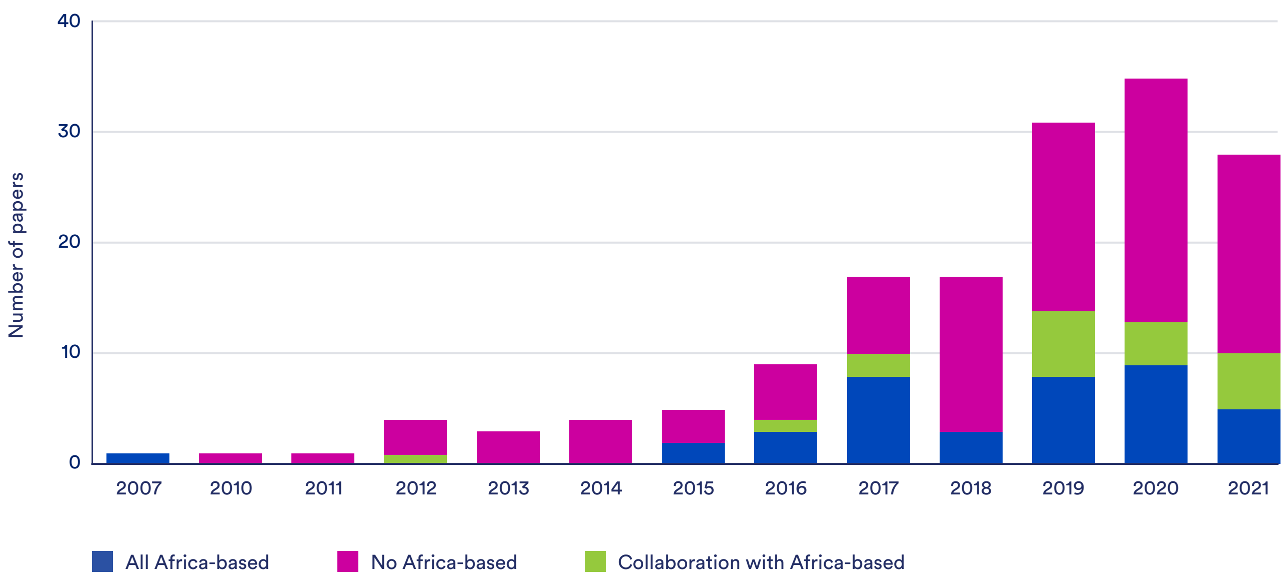
Appendix

7.1 Significance of Correlations with Regression

We regress the share of the papers on each of the proxies that we use for the country size to check whether the correlations are significant. The results show that correlations with GDP and population are high and significant[1] while that of the CO_2 emissions per capita are moderate and significant.[2] The correlation with the electricity consumption per capita and that of the CO_2 emissions is low and significant.[3] We do not find a significant correlation between country coverage and GDP per capita.

7.2 Additional Figures and Tables

Figure 11: Distribution Over Years of the Number of Papers by the Geographical Affiliation of the Authors



[1] The coefficients of regression are respectively, 0.95*** and 0.81***, with "***" corresponding to 1% for the degree of significance.

[2] The coefficient of regression is 0.50*, with "*" corresponding to 10% for the degree of significance.

[3] The coefficients of regression are 0.0008* and 0.00004***, respectively, with "*" and "***" corresponding to 10% and 1% for the degree of significance, respectively.

7.3 List of Papers Included in the Analysis

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7.4 Details on the Methodology

7.4.1 Example of Search: Scopus

TITLE-ABS-KEY(ssa OR africa* OR Nigeria OR Ethiopia OR congo* OR "Democratic Republic of the Congo" OR Egypt OR "South Africa" OR Tanzania OR Kenya OR Uganda OR Algeria OR Sudan OR Morocco OR Mozambique OR Ghana OR Angola OR Somalia OR "Ivory Coast" OR Madagascar OR Cameroon OR "Burkina Faso" OR Niger OR Malawi OR Zambia OR Mali OR Senegal OR Zimbabwe OR Chad OR Tunisia OR Guinea OR Rwanda OR Benin OR Burundi OR "South Sudan" OR Eritrea OR "Sierra Leone" OR Togo OR Libya OR "Central African Republic" OR Mauritania OR "Republic of the Congo" OR Liberia OR Namibia OR Botswana OR Lesotho OR Gambia OR Gabon OR "Guinea-Bissau" OR Mauritius OR "Equatorial Guinea" OR Eswatini OR Swaziland OR Djibouti OR Comoros OR "Cape Verde" OR "São Tomé and Príncipe" OR Seychelles) AND ("Energy transition"* OR "Low carbon transition"* OR decarboni* OR "Energy pathway"* OR "Low carbon pathway"* OR "Net-zero"*) AND (model* OR scenario*) PUBYEAR > 1999

7.4.2 Data Extraction Template in Covidence

General Information

1. **ID number**
   Identification number from Covidence.

Authorship

2. **Author 1 affiliation**
   Document the author affiliation. In case there are multiple affiliations, use the African-based affiliation or the first listed if none in Africa.
3. **Author 2 affiliation**
   Document the author affiliation. In case there are multiple affiliations, use the African-based affiliation or the first listed if none in Africa.
4. **Author 3 affiliation**
   Document the author affiliation. In case there are multiple affiliations, use the African-based affiliation or the first listed if none in Africa.
5. **Author 4 affiliation**
   Document the author affiliation. In case there are multiple affiliations, use the African-based affiliation or the first listed if none in Africa.
6. **Author 5 affiliation**
   Document the author affiliation. In case there are multiple affiliations, use the African-based affiliation or the first listed if none in Africa.

Geographical scope

7. **Geographical scope**
   1. Africa Region exclusively
   2. Includes Africa Region
   3. Multiple African countries exclusively
   4. One African country only
   5. Includes selected African countries
8. **List of African subregions or countries covered**
9. **Economic development implications**
   Are the development objectives explicitly discussed as part of the hypothesis (e.g., Growth, Employment or jobs, Poverty, Income)?
   1. Yes
   2. No
10. **Economic assumptions**
    What are the economic assumptions used in the model? (e.g., list highest and lowest growth levels)
11. **Model classification**
    1. **"Techno-economic systems:** defined by energy flows associated with energy extraction, conversion and use processes involved in energy production and consumption as coordinated by energy markets;
    2. **Socio-technical systems:** delineated by knowledge, practices and networks associated with energy technologies; and networks of developers, manufacturers and installers of solar PV panels, maps of shale gas locations, patents for electric vehicle batteries, and household practices of using heat pumps or car sharing;
    3. **Systems of political actions:** influencing energy-related policies;
    4. **Combinaison of previously listed systems"**
       1. Techno-economic systems
       2. Socio-technical systems
       3. Systems of political actions
       4. Combinaison of previously listed systems
       5. Other
12. **Discussion of sociological aspects of energy transition**
    Does the paper explicitly discuss sociological aspects?
    1. Yes
    2. No

13. Discussion of political aspects of energy transition
Does the paper explicitly discuss political aspects?

1. Yes
2. No

14. Model approach

1. **"Top-down** – top-down with endogenous assessment of economic and societal effects (i.e., input-output models, econometric models, computable general equilibrium models and system dynamics).
   The approach follows the economic approach, considering macroeconomic relationships and long-term changes
2. **Bottom-up** – Bottom-up with higher technological detail (i.e., partial equilibrium models, optimization models, simulation models, multi-agent models).
   It is an engineering approach, based on detailed technological descriptions of the energy system.
3. **Hybrid** (as a combination of Top-down and Bottom-up), when assessing the integration of variable renewables, both long-term changes and technological properties are of high importance.
4. **Not relevant** – given the model classification"

15. Methodology

1. **"Simulation:** the method simulates an energy-system based on specified equations and characteristics... often bottom-up models.
2. **Agent-based simulation:** a specific case of models where actors participating in e.g. the electricity market are modelled explicitly as agents with distinct strategies and behaviour.
3. **Optimisation:** optimise a given quantity (system operation or investment, or several aspects simultaneously)...Mostly linear programming (LP) approach (max or min), subject to a set of constraints (e.g. balancing the supply and demand in the grid)... Mixed-integer linear programming (MILP) forces certain variables to be integral, which can be useful when for example optimising how many power plants or the number of wind turbines one should invest in... Non-linear, i.e. the objective function or constraints are non-linear. Heuristic optimisation models do not necessarily find the optimum solution. By simple and fast methods, such as the Covariance Matrix Adaption Evolution Strategy (CMA-ES), the optimal solution can be approximated.
4. **Equilibrium:** An economic approach, modeling the energy sector as a part of the whole economy and studies how it relates to the rest of the economy. General equilibrium models, or computable general equilibrium models (CGE), consider the whole economy. They determine the equilibrium across all markets and determine important economic parameters such as the gross domestic product (GDP) endogenously. Partial equilibrium models (PE) focus on balancing one market, in this case the energy or electricity market, with the rest of the economy not modelled.
5. **Econometrics**
6. **Machine learning**
7. **Combinaison of methods"**
   1. Simulation
   2. Agent-based simulation
   3. Optimisation
   4. Equilibrium
   5. Combinaison of methods
   6. Econometrics
   7. Machine learning
   8. Other

16. Level of data disaggregation: National
Does the model use the data at the national (macro) level?

1. Yes
2. No

17. Level of data disaggregation: Household
Does the model use the data at the household (micro) level?

1. Yes
2. No

18. Level of data disaggregation: Firms
Does the model use the data at the firms (micro) level?

1. Yes
2. No

19. Level of data disaggregation: Sector
Does the model use the data at the sector level?

1. Yes
2. No

20. Level of data disaggregation: Subnational
Does the model use the data at the subnational level?

1. Yes
2. No

21. **Sources of data**
    What are the sources of data used in the model? (Use abbreviation like WDI, IEA, DHS, LSMS, etc.)

22. **Energy pathways (mix, demand, supply)**
    Do the results or outcomes of interest include "Energy pathways (mix, demand, supply)"?

    1. Yes
    2. No

23. **Emissions pathways (CO_2 emissions)**
    Do the results or outcomes of interest include "Emissions (CO_2 emissions)"?

    1. Yes
    2. No

24. **Development pathways(Growth, poverty)**
    Do the results or outcomes of interest include "Development (Growth, poverty)"?

    1. Yes
    2. No

25. **Projection horizon**
    What is the time horizon of the projection?

26. **Number of scenarios assessed**
    What is the number of scenarios considered in the paper?

27. **Scenario path details**
    Are the pathways provided on the year-by-year basis instead of only for the final year?

    1. Yes
    2. No

28. **Discussion of pathways**
    Is any point in the pathways discussed other than the end-point?

    1. Yes
    2. No

29. **Years of pathways discussed**
    What are the points (years) discussed in the pathways other than the end-point?

30. **Technology restrictions**
    Are the energy technologies restricted ex-ante?

    1. Yes
    2. No

31. **Energy technologies included in the model**
    What are the energy technology included in the analysis? (e.g., Wind, solar, nuclear, etc.)

32. **Energy technology cost**
    Does the model discuss explicitly the energy technology cost?

    1. Yes
    2. No

33. **Energy transition cost**
    Does the model discuss explicitly the energy transition cost? (e.g., cost in addition to the technology cost)

    1. Yes
    2. No

34. **Calculation of energy cost**
    Does the model use context-related information to calculate the energy technology cost instead of using cost assumptions?

    1. Yes
    2. No

35. **Cost of energy technology**
    What is the cost of the energy technology used in the model?

7.4.3 Additional Data

a. **Classification:** for each author, provide the following classification based on their affiliation
    1. Academic institution within Africa
    2. Academic institution outside Africa
    3. International organization (WB, IMF, UN, OECD, IRENA, IEA)
    4. Regional organizations within Africa (AfDB, ECOWAS, UNECA)
    5. Regional organizations outside Africa (IADB, ADB)
    6. Non-Governmental Organization within Africa
    7. Non-Governmental Organization outside Africa
    8. Public institutions (Ministry, Government Agencies, etc.)

b. **For each author,** provide the following rank of the institution (using SCIMAGO ranking: https://www.scimagoir.com/rankings.php?ranking=Research) based on their affiliation

c. **Academic Influence 1:** For each of the papers, provide the number of citations (using google scholar)

d. **Academic Influence 2:** For each of the papers, provide the impact factor of the journal (provided on the journal website)

e. **Academic Influence 3:** for author 1, provide the number of citations (using google scholar)