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The role of hydropower in the broader context of climate change and sustainable development. Evidence from sub-Saharan Africa

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ABSTRACT

Nell’arco degli ultimi decenni, nessuna sfida ha richiesto un così chiaro impegno comune a livello globale come il cambiamento climatico. Visto il rilevante peso dell’energia da combustibili fossili nell’emissione di CO2 e nel conseguente ‘effetto serra’, diverse istituzioni internazionali hanno reso chiaro l’obiettivo di generare sempre più energia con fonti rinnovabili e pulite. Questa discussione risulta particolarmente importante nei paesi in cui il fenomeno dell’industrializzazione è ancora in corso. Secondo le statistiche concernenti la povertà energetica e l’elettrificazione, l’Africa sub-Sahariana ospita gran parte della popolazione mondiale ad oggi priva di accesso all’energia. Questa percentuale è destinata a crescere, poiché gli investimenti in ambito energetico non riescono a tenere il passo con la crescita economica e demografica presente in questa regione. L’accesso all’energia, che sia pulita, rinnovabile ed economica, è ad oggi inserito tra gli obiettivi di sviluppo sostenibile (SDG). L’energia è pertanto riconosciuta come un fattore fondamentale allo sviluppo economico e sociale, con numerose implicazioni in diversi aspetti della società (nel secondo capitolo è fornita una breve rassegna dei benefici dell’elettrificazioni). Al fine di aumentare la capacità energetica nazionale per incrementare l’accesso all’elettricità, vari paesi sub-Sahariani hanno sfruttato il potenziale idroelettrico latente investendo nella costruzione di dighe. Nella letteratura scientifica contemporanea, la costruzione di dighe è stata frequente oggetto di dibattito per via degli elevati impatti sociali e ambientali, nonostante la necessità di energia pulita derivata dal cambiamento climatico. La creazione di bacini idrici artificiali è spesso causa di tensione politica a livello sia locale che nazionale, visti gli impatti negativi che la costruzione di dighe trasferisce a valle in bacini fluviali transfrontalieri. Sul piano delle relazioni internazionali, le dighe idroelettriche vanno a modificare l’assetto idrologico dei fiumi transfrontalieri, mettendo spesso in discussione la sovranità nazionale delle nazioni a fondo valle come nel caso del corrente conflitto tra Etiopia ed Egitto. Sebbene i conflitti diretti tra nazioni su questo tema siano estremamente rari, si fa via via più evidente la necessità di una gestione accorta e comune dei corsi d’acqua comuni, a causa della crescente domanda di acqua e delle incertezze climatiche.

Pur rimanendo la principale fonte di energia rinnovabile, negli ultimi anni l’aumento delle temperature ha portato alcuni studiosi a ricercare gli impatti del cambiamento climatico sulle dighe, e come i fenomeni climatici estremi, come siccità e alluvioni, possano influenzare la

capacità di generazione idroelettrica. Nelle più recenti previsioni fatte dall'IPCC, si prevede come alcune regioni particolarmente aride dell'Africa sub-Sahariana, siano destinate a diventare più aride, mentre le regioni più umide a diventare più umide. Ciò comporterebbe periodi di precipitazione più erratici, andando ad incrementare i rischi legati ai fenomeni di siccità e alluvioni. Alla luce della stretta dipendenza da fonti idroelettriche e da un costante input di acqua per la generazione di elettricità, l'aumento dell'evaporazione e la ridotta frequenza di pioggia causerebbero non solo disagi interni alle nazioni (uso competitivo dell'acqua con l'agricoltura e carenza di energia) ma anche internazionali andando ad aumentare le tensioni ed i conflitti già esistenti tra i vari paesi sovrani lungo i bacini transfrontalieri. Le interconnessioni con una varietà di aspetti sociali, economici, politici, antropologici e ambientali hanno da tempo richiesto un nuovo modo di approcciare i sistemi naturali in rapporto alla società umana. La struttura di questo rapporto sarà severamente messa in discussione dai futuri aspetti del cambiamento climatico, generando maggiori pressioni sui sistemi idrici ed energetici di quelle esistenti già oggi. Vista l'alta dipendenza da energia idroelettrica dei paesi del sub-Sahara, nel corso di questa tesi si cercherà di fare più attenzione possibile alla specifica interazione tra clima, acqua ed energia in quanto sistemi interconnessi e capaci di influenzarsi a vicenda.

L'obiettivo di questa tesi è discutere dell'interazione tra Clima-Acqua-Energia dalla prospettiva della dipendenza idroelettrica nell'Africa sub-Sahariana, con l'obiettivo specifico di esplorare la relazione di eventi climatici estremi come le siccità e la generazione idroelettrica. Nello specifico, si cerca di offrire una valutazione specifica della regione legata allo sviluppo energetico basato sul rinnovabile idroelettrico, fornendo una prospettiva dettagliata dei molteplici benefici derivanti dalla crescita energetica a basso costo e dall'aumentata capacità idrica, ma anche dei risvolti negativi per la 'sicurezza idrica ed energetica' dei vari paesi discussi e delle storiche tensioni regionali. Successivamente, attraverso l'uso di dati satellitari si cerca una correlazione tra siccità e illuminazione notturna nell'arco di anni tra il 1992 ed il 2013. Attraverso una analisi quantitativa di dati, si dimostra l'esistenza di una effettiva influenza del clima sulla generazione energetica (e di conseguenza sulle risorse idriche) offrendo un piccolo contributo alla letteratura scientifica sul tema delle interazioni tra sistemi climatici, idrici ed energetici. Infine, attraverso l'utilizzo di dati satellitari ad alta precisione, si offre una piccolo contributo sull'efficacia dei dati telerilevati, nel supportare e sostenere la ricerca nell'ambito delle scienze sociali.

INTRODUCTION

Historically, energy has been a fundamental component of human society and electricity has become a fundamental component of modern industrialized society and for decent living conditions.[i] Fossil fuels like coal, oil, and natural gas have traditionally held a cardinal role in the social and economic development of every modern nation (Pomeranz, 2000; O'Rourke and Ferninhough, 2014). [ii] [iii] During the recent decades, the scientific community has provided irrefutable evidence of the link between increasing temperatures and greenhouse gas emissions (IPCC, 2007; IPCC, 2021).[iv][v] Electricity generation is the largest single source of greenhouse gas emissions, contributing globally to 25% of the total.[vi] While this figure clarifies the priority of phasing out of fossil fuels from the global energy mix, this situation has the potential to widen the already existing gap between developed and developing countries because developing regions still need to achieve universal electrification for their population. Considering the overall population without access, 13% live in South Asia, and around 77% live in Sub-Saharan Africa. As such, sub-Saharan Africa alone represents three-quarters of the global population with an electricity deficit, with 46.7% of the total sub-Saharan Africa population living without access to the most basic form of modern electrification.[vii] Distribution even inside this continent may be striking, with the connections to the national grid among the urban population (72%) outnumbering those in rural areas (28%).[viii] Different sub-Saharan countries have progressively increased their electricity generation capacity relying on one specific cheap, carbon-free, and at the same time reliable source of energy: Hydropower. Nevertheless, hydropower has also received much attention for its costly negative externalities on different social, environmental aspects.

The interlinkages with a variety of social, economic, political, anthropological, and environmental aspects have long called for a nexus approach to understand the intricacies and ramifications of the influencing factors in water and energy systems. During the last decades, the climate has been recognized as a fundamental influencing factor for water and energy systems, thus generating a new Climate-Water-Energy (CWE) nexus approach. Most sub-Saharan African countries are overdependent on hydropower, and the recent scientific evidence on climate change underlined how this region will likely witness a sensible increase in temperatures and extreme climatic events. Increased evaporation of reservoirs and disruption in inter-seasonal rainfall will likely increase drought events in magnitude and frequency. This forecasted situation will likely result in severe socio-economic impacts, which will generate spill-over effects on different aspects of human society. In the course of this thesis, the concept of human security will be addressed for this matter on different perspectives. In the management of transboundary water basins, national governments have to keep into account the possible tensions that may be generated at the local (increased water use competition with other sectors, environmental disruption, human displacement) and international level (transnational water security concerns). Taking into account the human-security aspect of the CWE nexus, creates a wider and complete picture of the dynamics generated by the interactions between extreme climatic events and reduced electricity supply, with all the relevant consequences described in the first part of the thesis.

The objective of this thesis is to fill the gap in the literature around the Climate-Water-Energy nexus with a specific aim of exploring the relationship between hydroelectricity generation and extreme climatic events. After providing literary-backed scientific evidence of the structural conditions of the CWE systems in sub-Saharan Africa, I gathered and harmonized remote-sensed data on luminosity at night, on the spatial distribution of hydropower plants with data on precipitations and indicators of droughts and floods to explore whether there exists a positive or negative relationship, measured with the statistical concept of correlation, between hydropower energy supply and extreme climatic events. This research will contribute to the current literature in two ways. First, it offers a broader and more comprehensive assessment of the pros and cons of development based on hydropower from a human security perspective and accounting for the region-specific extreme climatic events and their interaction within the water and energy systems in sub-Saharan Africa. Second, this thesis demonstrates how remote-sensed open data offers an untapped potential to make progress in social sciences and humanities research.[ix] The first part of this endeavor aims at providing qualitative evidence of the region-specific CWE nexus, backed by a substantial amount of empirical evidence on the main advantages and risks that an overreliance on hydroelectricity in the energy mix may entail in the region. The second part describes the effort of collecting remote-sensed evidence of drought events and energy supply in urban areas of sub-Saharan Africa and discusses the results regarding the relationship between these two variables.

This thesis will be structured as follows. The first chapter provides a literary review of the broader water-energy nexus, water availability, and expected effects of climate change, dam-building, and the main social, economic, political, and environmental impacts and externalities generated by hydropower projects. The literature provided underlines the interaction between hydropower and human security on several dimensions of social sciences. The chapter outlines how water and energy systems interact, and how in the water-energy nexus framework, water scarcity amplifies the structural vulnerabilities of human security in the region. The framework/assessment is based on a solid analysis of primary and secondary sources, and peer-reviewed literature is created.

Following in Chapter 2 is provided a region-specific perspective on climate and hydropower. In this chapter, the first aim is to discuss the benefits and advantages provided by hydropower dams, thus providing a possible explanation about why national governments tend to favor these large infrastructural projects notwithstanding the impacts on human security provided in the chapter before. The second point of discussion is created around the region-specific climatic conditions of the sub-Saharan African continent. In brief, by considering the regional climate system in the water-energy nexus, the picture around hydropower becomes extremely more realistic and favors a comparison between the economic and social benefits provided by increasing water capacity, energy generation, and mitigating extreme events (only in case of multipurpose dams), and the risks linked to human security such as trans-national political tensions, social grievances, and environmental impacts.

In Chapter 3, the main principles behind remote-sensed data and how they will be used are provided. The aim is to express in relatively simple terms how the climatic and data on nighttime luminosity, a proxy for electricity access, are collected, processed, and finally used in Chapter IV, which will present the results. A nit-picked literary review is provided in Chapter III for both the SPEI (Standard Precipitation Evapotranspiration Index) and SPI (Standard Precipitation Index) indexes, and for the nighttime illumination radiance (NTL) datasets, to explain how they are used, and why they may work as an efficient substitute of respectively extreme climatic events (namely, droughts and floods), and energy supply to urban areas in sub-Saharan Africa.

The quantitative analysis of the data presented in Chapter 3 is finally explained and discussed in Chapter 4. This chapter aims at providing data-based evidence of the Climate-Water-Energy nexus described in the previous chapters, thus providing confirmation of the theoretical considerations regarding the relationship between climate impacts on energy supply. The positive correlation found further advances the literature on NTL as an efficient surrogate and predictor of energy supply, especially in geographic contexts plagued by 'data-poverty'. Finally, it is provided the statistical correlation between the two climatic indexes described in Chapter 3 and the NTL dataset. The visual analysis of the data reveals the existence of a clear positive correlation between drought events and reduced energy supply. Some notable cases are provided with a possible explanation, such as the case of Ethiopia and the existence of a negative correlation between the extreme events and reduced energy supply, thus suggesting how flood events increase the energy system vulnerability, rather than drought events.

Finally, Chapter 5 links the qualitative and quantitative analyses conducted in the previous chapter in order to derive some general conclusions. The main contribution of the work is to clarify how in hydropower-reliant countries, the concept of human security is not limited to considerations related to the water and energy systems, but it is also inevitably linked to climate considerations, which are made evident by the presence of a quantitative remote-sensed correlation between the sensible reduction of final energy use and presence of drought events.

1. Literary Review

“If I have seen further, it is by standing on [the] shoulders of Giants.”

Sir Isaac Newton

1.1 Chapter introduction

During the last decades, the global effort against climate change has become a fundamental point of the academic and political debate, especially now that scientific research has provided empirical evidence on the magnitude and the unequivocal human-induced contribution to this phenomenon (IPCC, 2007). The intense debate sparked between academic and decision-making institutions led to a global discussion that is not limited anymore to the environmental and natural science sectors but started progressively including economics, social, political, legal, and anthropological science in their discussion. The nature of modern-day global problems such as that of anthropogenic global warming necessarily requires a nexus approach to correctly understand the possible impacts, solutions, and eventually opportunities related to this century-defining event. With the objective to further comprehend the specific question of hydropower and its implication for the Water and Energy Systems in the nexus approach, this chapter will provide an overview of the state-of-the-art of academic and scientific literature on the topic.

1.2 Water-Energy-Food Nexus

The existence of interlinkages and interdependence of energy and water systems on a global level are both evident and insurmountable. From an energetical perspective, hydropower generation, thermo-electrical, and nuclear power plant cooling depend on water as a fundamental input for energy production. At the same time, significant amounts of energy are dedicated to different forms of water treatment, conveyance, and disposal, which may include for example irrigation and groundwater pumping. Both energy and water are necessary inputs for food production, which apart from the obvious nutritional function, may provide energy through biomass and biofuels production. The interaction between these interlinked resource systems has been defined as the “Water-Energy-Food nexus” (WEF).

The definition of ‘nexus’ found in the Merriam-Webster online dictionary is, as reported: (a) connection, link, and also a causal link; (b) a connected group or series and (c) center, focus.[x] The existence of a Water-Food-Energy (WFE) Nexus was first recognized during the Bonn 2011 Conference, organized by the German Federal Government as a contribution towards the United Nations Conference on Sustainable Development (Rio + 20).[xi] The main premise around the WEF nexus is that:

a. Water, energy, and food resources are under strain due to social and climate change. (UNECE, 2018).[xii]
b. By 2030, due to growing consumption and population demand for water, energy, and food, consumption is estimated to increase by 40%, 50%, and 35% respectively (USNIC, 2012).[xiii]
c. Complex interactions among this nexus will increase trade-offs and conflicts (Endo and Oh, 2018).[xiv]

In the recent literature, the importance of accounting for cross-system implications and dependencies has been underlined. With different approaches analyzing the scope of impacts and interactions in this WEF nexus Howells and co-authors (2013) [xv] called attention to the importance of climate in evaluating the WEF interlinkages. Biggs et al (2015) [xvi] underlined how climate is not a resource system in itself, but recognized how it affects, and is affected by, the resource systems considered in the WEF approach, thus calling for a revisitation of this framework towards a “Climate-Land-Energy-Water” (CLEW) nexus (Eunice Pereira et al, 2021).[xvii] In Bazilian et al (2011), the CLEW framework has the objective to support decision-makers with policy assessment, harmonization, and integration, and support experts with more precise technology assessments and scenario development. [xviii] In the context of the WEF framework, hydropower is often cited as a critical element at the core of this three-way system (Hoff, 2011). While recognizing the benefits that hydropower may provide with the increased water management, energy generation, and food security, Albrecht, Crootof, and Scott (2018) in their review point out the double-edged characteristic of dam-building.[xix] The risks behind this technology are well-known and poor planning may conequentely result in the worsening condition of different aspects of the WEF system, something especially true in the CLEW context, considering the enhanced evaporation and increased drought events due to climate change.

1.3 Resources and conflict interlinkages

In the context of institutional and international relations dialogue, the WEF nexus is framed as a hard (military) security issue due to the impact that water, food, and energy all have on prosperity and peace in a country (Endo and Oh, 2018).[xx] All the three systems inside the WEF nexus form an important part of the research linked to security and conflict issues from climate change or external political entities. There is widespread empirical evidence suggesting the impacts of climate change on the availability of water, food, and energy through the intensification of extreme events like floods, droughts, and rising sea levels, which consequently increase the possibility of human conflict (Howells et al, 2013).[xxi] This connection is reinforced by the common perception of climate change as a 'threat multiplier' in human conflict. Recent scientific evidence seems to support the correlation between human conflicts and scarcity of water, energy, and food, linking these two sides in solid causal relation (Burke et al., 2009; Devitt and Tol, 2012; Edward, Satyanath and Sergenti, 2004).[xxii][xxiii][xxiv] According to Redclift (2001), the association of resources with potential conflicts led to a shift from the traditional idea of security, usually perceived as lack of, or safety from, military threats to a concept understood as a chain of "natural" processes (such as water scarcity) and the relative impacts on physical security and welfare.[xxv]

Particular attention in the literature related to conflict has been given to water-induced conflicts. Water scarcity is quite common, with 700 million people experiencing it, and 1.6 billion people subject to economic water shortage (countries lacking sufficient infrastructure to use waters from aquifers and rivers).[xxvi] The number of average water conflicts each year went from 0.5 to 32.3 in the period of time between 1900-2017 (Gleick, 2013).[xxvii] In Keskinen et al. (2016), it is expressed how value chains generated by resource flows tend to cross transnational boundaries much more easily than commonly thought.[xxviii] Among others, Galgano and Krakowa (2010) underline how water, food, and energy are not only intertwined in a causal relationship but their management and governance is inherently intersectoral and transnational, as is envisaged by different nexus approaches.[xxix] Hakala et al (2013), emphasize the need for environmental considerations in the context of security and reliability.[xxx] With her colleagues, Hakala underlines the dual nature of environmental security, as it influences human security, but cannot be framed in a traditional security perspective. Due to the complexity of the interactions between the natural environment and human society, Giampietro and his colleagues (2013) produced a multi-scalar and cross-sectoral approach called "**MuSIASEM**", in order to improve the understanding of the new security considerations around climate change.[xxxi] This innovative approach has been put into practice and broadened by other scholars (Van Beck and Arriens, 2014; Keskinen, Sojamo, and Varis, 2019) revealing the need for the human-security sector, to embrace new patterns of risk assessment, improve multi-sectoral strategic intent, and increase interactions between researchers and policy-makers for a new comprehensive policy approach.[xxxii][xxxiii] Environmental threats have different dimensional perspectives that range from local to international. Transboundary river management is among the most researched environmental security issues with an international range. According to Lawford et al. (2013),[xxxiv] the main sources of transboundary river stress are:

(I) Climate Change (Kundzewicz et al., 2008);[xxxv]

(II) Political and Economic Change (Pahl-Wostl et al., 2012);[xxxvi]

(III) Regional and Economic Development (Vörösmarty et al., 2010);[xxxvii]

(IV) Demographics (Vörösmarty et al., 2010);

(V) Urbanization (Owen, 2011);[xxxviii]

(VI) Land Use change (Wagner et al., 2013);[xxxix]

(VII) Basin infrastructure.[xl][xli]

Concerning transnational resources like water basins, the academic debate on security issues began increasingly incorporating climate change considerations, creating the relatively new field of "environmental security" (United Nations Environment Programme and the Woodrow Wilson Center, 2004; Vogel and O'Brien, 2004).[xlii][xliii] The UNEP and Woodrow Wilson Center (2004) production specifically shed light on the increasing rate of conflict for pastoral communities living in sub-Saharan Africa, and how this is positively linked with the increase of extreme events like droughts, which aggravate food and water scarcity.

According to the FAO (2014), around 70% of water withdrawals and 30% of global energy are due to food production. By 2050, global food consumption is expected to undergo a 60% increase, and by 2035 energy demands will increase by 50% and irrigation needs by 10%.[xliv] While not keeping into account the possibility of technological advancement that will increase the efficiency of these resources, increased consumption may still stress already scarce resources, resulting in a stronger possibility of conflict. Fragile contexts characterized by lack of economic resources and growing demographic pressure have the highest potential of developing socio-political turmoil due to scarcity reasons (Almer et al., 2017; Raleigh and Urdal, 2007).[xlv][xlvi] In the specific case of water availability, hydropower may compete with agriculture in contexts of drought, leading to intra-national conflicts against local institutions (Vesco et al., 2020; Homer-Dixon, 1999).[xlvii][xlviii] While the topic of state failure and weak institutions is a still divisive issue, proof of pressure on water availability and demand is found in Boko et al (2007) with the longer dry periods and more erratic rainfall patterns expected to further pressure the agriculture, on which much of the sub-Saharan economies rely (IPCC, 2007). Hendrix and Salehyan, (2012) provide a historical relationship between social conflicts and rainfall, which due to climate change may create difficult conditions for the African continent. With a specific reference to drought influence on conflict, Theisen, Holtermann & Buhaug (2011–12)[xlix], used different drought measurements but found no specific evidence of a direct relationship between drought and civil conflict in Africa during the 1960–2004 period, placing the primary cause of intra-state conflict on political, and not environmental, reasons. Nevertheless, in their research Burke et al. (2009), found that temperature increases in Africa between 1981 and 2002 do have positive effects on the occurrence of civil war, due to drought impacts on agricultural production and economic welfare.[l] Thus, they calculate the statistical increase of temperature and the expected precipitation conditions, forecasting sustained growth in incidence of intra-state conflict unless certain agricultural improvements and welfare policies to protect the poorest are enacted. With around 50% of the sub-Saharan economy depending on agriculture (World Bank, 2009),[li] the impacts of climate change in the form of dryer or wetter scenarios make socio-economic conditions particularly vulnerable, due to the low adaptive capacity of the continent, seem to suggest a strong possibility of an increase in climate-related conflict in the continent. Sub-Saharan Africa is a continent characterized by chronic economic fragility, dependence on agriculture, ethnic fractionalization, and changing climatic conditions, leaving its population particularly vulnerable to social conflict (Theisen, 2017; Von Uexkull, 2014).[lii][liii] With cheap and reliable electricity production, low cost of management, and the multipurpose function of their wide artificial reservoirs, hydropower is usually regarded as a form of public investment to achieve economic development and some form of adaptive capacity to climate change through increased water and electricity access. In reality, the construction of hydropower plants in a shared water basin creates numerous negative impacts of local, national, transnational dimensions which are usually not accounted for in preliminary studies, and that may fuel conflict situations. The local dimension of conflict may be that of ethnic minorities protesting against local government institutions due to lack of appropriate compensation, aggravating the problem of ethnic division and impoverishment.[liv] On the national level and international level, a situation of political tension is generated with approaches that include direct military threats, occasional use of violence, and cooperative and diplomatic management of shared water resources. Homer-Dixon (1994) provides some examples of how the decreased quality of water in the river between Senegal and Mauritania created some international tension leading to ethnical violence, but other compelling examples of international scale conflict are present.[lv] Different subsets of actors have different relations to water, perceiving it as "simply another environmental input, water is regularly treated as a security issue, a gift of nature, or a focal point for local society" (Wolf, 2007).[lvi] Dam-building may develop a process of progressive military securitization of water, which creates different responses ranging from political tensions to terrorist and military action in a conflict. [lvii][lviii][lix] Finally, Gleick and Heberger's "Water Conflict Chronology" (1993), provides different examples of how dams and reservoirs have been historically weaponized in ancient and modern conflicts.

1.4 Increased water and energy access through dam-building

Throughout the world, sufficient amounts of freshwater are present to meet human demand. Availability and demand are however dependent on spatial and temporal variations, which create material scarcity of water in specific geographic locations at specific times of the year.[lx] Intra-annual variations of consumption and availability of both fresh surface water and groundwater, create water scarcity, which may be aggravated by a wide range of socio-economic and environmental factors.[lxi] Excluding Antarctica, 45% of the earth's land surface is covered by approximately 276 transboundary river basins (TFDD 2014, Wolf 1993).[lxii][lxiii] Transboundary rivers are rivers shared by two or more countries, from which 40% of the population depends for their livelihood and provide 60% of the world's freshwater supply (United Nations World Water Development Report, 2015).[lxiv] Water scarcity in sub-Saharan Africa is not physical scarcity in the sense of material lack to satisfy all demand, but mostly due to economic reasons with lack of investment in infrastructure and technology enabling the satisfaction of human demand.[lxv] Keeping into account the water-energy nexus, and the widespread lack of access to clean water and electricity in sub-Saharan Africa, dam-building offers a tempting answer to tackle both problems. In an analysis of 163 countries made by Brown and Lall (2006), it was found a strong correlation between variability in rainfall and lower GDP, thus suggesting that improvements in water storage were most needed in poorer countries.[lxvi] Agriculture and water supply in Africa are highly inefficient, with most of the crops being primarily rain-fed and consuming more water and land resources than comparative footprint benchmarks of other countries.[lxvii] The inter-annual variability of precipitation, climate warming, and human activities may affect hydrological processes and water allocation patterns, changing flood frequencies and intensity (Kabanda and Palamuleni, 2013; Vormoor et al., 2014).[lxviii][lxix] With a spatial and temporal distribution of flood disasters in African countries calculated through ArcGIS 9.3, Li et al. (2016)[lxx] concluded how East Africa is the geographic region more subject to flood disasters frequency with a high correlation to deaths and damages. Of the seven most flood-prone countries, Ethiopia, Sudan, and Tanzania are included in the panel of countries considered in this thesis. Keeping into account the unpredictable nature of rainfall and precipitation in Africa, and the tendency to both periodic floods and droughts, the United Nations Economic Commission for Africa (UN ECA, 2000)[lxxi] points out the importance of sustainable use and efficient water storage as key to solving water scarcity in the continent.

In the last 50 years, the phenomenon of dam-building has grown in intensity all over the world increasing in number from 5,000 in 1950 to 50.000 in 2006 (Richter et al. 2010). More than 70% of global basins and rivers are dammed for different purposes, among which flood control, water storage, water supply, and electricity generation (Kummu and Varis 2007).[lxxii] IEA (2021) accounts for over 16% of global electricity generated by hydropower.[lxxiii] Chao, Wu, and Li (2008) calculated that the creation of artificial basins through dam-building led to an increase of about 28% of global water supplies, with an estimated 8,000 km3 of water added.[lxxiv]

This form of improved water management also provided obvious positive impacts to food production. Overall, an estimated 12-16% of water preserved in dams is destined for agricultural purposes (Richter et al. 2010). This creates spillover positive effects of dams on agriculture which extends to the general socio-economic conditions of a specific region. The great exploitable potential is found along the Congo, the Nile, and the Zambezi basin, with the specific hydropower potential capacity expressed in Terawatt hour (TW/h) as seen in the graph below (Zhou et al, 2015).[lxxv] Figure 1 visually represents over a histogram the overall unexploited potential in the sub-Saharan region present in the discussed review.

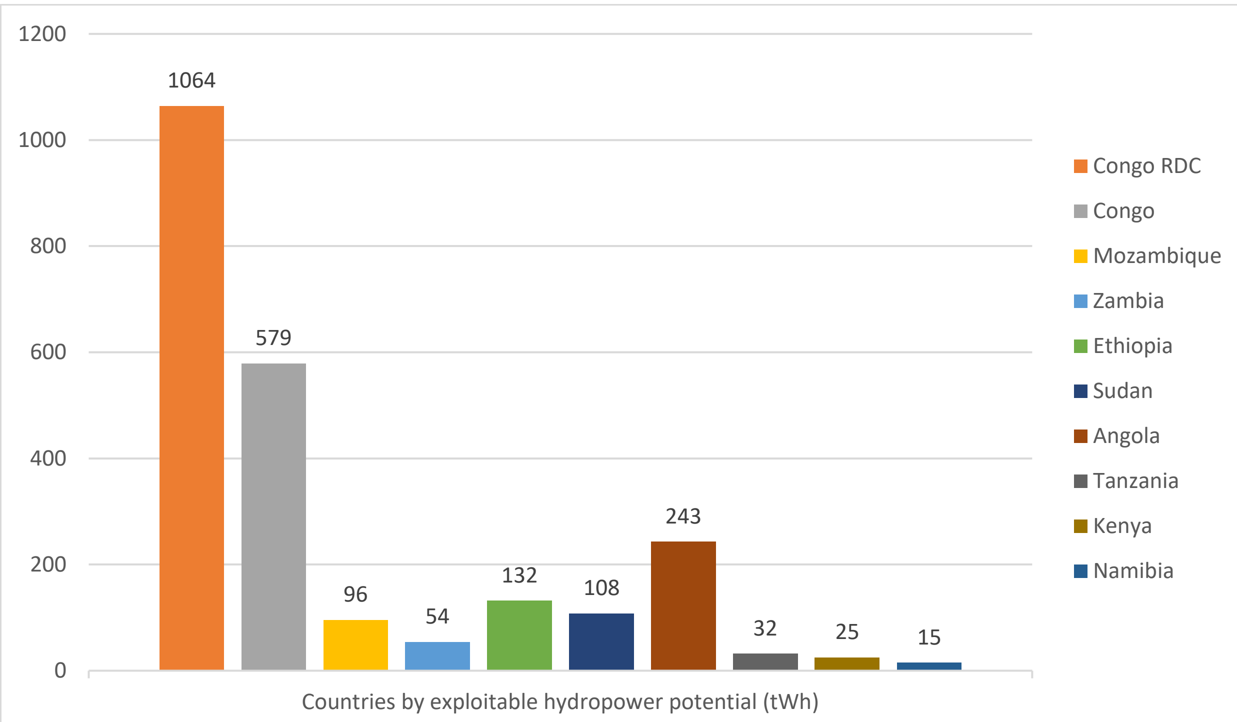


Figure 1: Histogram of countries by exploitable hydropower potential measured in Terawatt hours (TWh). Source: Zhou et al., 2015

Among the other benefits already discussed, hydropower holds specific advantages in terms of power plant durability and efficiency compared to other forms of electricity generation, cheap costs of both generation and management, and generally vast storage of energy in reservoirs for both pumped storage and conventional dams (IHA, 2003).[lxxvi] In the context of sub-Saharan low-income countries, the International Energy Agency (IEA, 2014) indicated cheap costs and long-term reliable electricity generation as extremely important tools in the fight against energy poverty in the continent.[lxxviilxxviii]

According to Egré and Milewski (2002), the main strategic advantage in adding hydropower capacity to an energy mix lies in the ability to provide both base and peak demand of energy.[lxxix] Such flexibility in supply provides specific technical advantages that enable hydropower plants to cover both baseloads in water-abundant regions, and peak load generation through pumped storage or large dams, allowing a much more flexible generation compared to nuclear, coal, or oil power plants. Williams and Stephen's (2006) analysis shows how hydropower is particularly appealing for governments in developing countries investing in energy infrastructure. Using a cost-benefit analysis (CBA), they demonstrate how hydropower provides socio-economic benefits for governments and citizens in being cheap, reliable, and comparatively cheaper in rural communities (specifically concerning micro or pico-scale plants). This CBA by the admission of the authors does not keep into account loss of ecosystems, direct benefits to electricity users through time-saving equipment, trickle-down effects of industrial activity in rural areas and potential to improve schools and health facilities, and finally additional benefits from fisheries, flood control, and irrigation.[lxxx]

Ziv et al. (2012) manage to depict a clearer picture of how grave environmental impacts on biodiversity in a dammed river is more a matter of choice than a precondition of dam-building, stating with the geospatial analysis how trade-offs are not so clear-cut.[lxxxi] According to Wichelns (2014) investing in large conventional dams provides important economic rents to the owner (both private companies and national governments) which are collected through taxation and distributed to the population by the disbursement of public funds.[lxxxii] Royalties on electricity exports, notably frequent for countries with extremely high potential, would give access to funds that could be used towards important public projects necessary to accommodate the trends of growing population and consumption. Economic rents are spread to customers, as farmers with access to irrigation water have the opportunity to produce more crops and higher yields, increasing the land value.[lxxxiii] Finally, concerning the potential increase in electricity generation by untapping hydropotential, different institutional objectives could be achieved. Mc Collum et al., (2018) show the fundamental embeddedness of the SDG 7 to "Ensure access to affordable, reliable, sustainable, and modern energy for all", with all the other SDGs in both positive and negative relationships.[lxxxiv]

Generally, plants are classified based on the capacity of production or by the infrastructural characteristics of the single plant. The physics behind hydroelectric generation involves kinetic and potential energy. Both are used in different forms in the three main types of hydropower generation plants: run-of-the-river, pumped storage, and conventional dams. Run-of-the-river (RoR) have little or no active storage of water inflows and depend on the kinetic energy produced by the river flow and are moderately influenced by drought-related events due to river flow speed being affected by abundance or scarcity of water. Pumped storage plants act as hydroelectric generators built as means to store electrical energy, as they do not generate net electricity. The bulk of hydropower generation is produced by conventional dams, which rely on the potential energy derived from the volume and the difference in height between the starting water input and the final water outflow (namely, the ***head***). There is no clear-cut definition of a ***large dam***, however, the one used throughout this thesis will be that proposed by ICOLD:

"A dam with a height of 15 meters or greater from lowest foundation to crest or a dam between 5 meters and 15 meters impounding more than 3 million cubic meters".[lxxxv]

Careful considerations must also be made around the collaborative management of transboundary rivers. In a case study focused on the Grand Ethiopian Renaissance Dam (GERD) in Ethiopia, Basheer et al (2021) describe how coordinating the different countries in the selected transboundary basin (the Nile river in this case), would create socio-economic gains for all nations up-and downstream. By coordinating and communicating water flows from GERD, Ethiopia may achieve an increase in total electricity generation. Meanwhile, both Sudan and Egypt would stand to gain economically thanks to extended livelihoods of their dams (GERD would trap massive amounts of sedimentation), and increased water security during multiyear drought periods, thanks to the immense reserve upstream enclosed by the GERD. According to Basheer's team, this would resolve the current political tensions create stronger incentives to collaboration between the riparian countries thanks to the coordination in water management.[lxxxvi] Finally, different researches recognize the importance of answering the lack of access to electricity in sub-Saharan Africa, as a way to break the historical socio-economic deadlock of the population. As the hardest part of tackling the electrification process is achieving access for the rural population, both Eberhard et al., (2008), and Kaunda et al. (2012), recognize how small and mini-scale hydropower projects may be the key towards achieving sustainable and reliable rural electrification. Both the reliability in electricity generation, and the flexibility in the connection to national-grid, small-scale grid, or stand-alone power systems make small-hydro projects a possible solution towards universal electrification.[lxxxvii][lxxxviii]

1.5 Energy Access Benefits

There has been strong academic interest in investigating the positive relationship between socio-economic benefits and access to electricity. While the causal relationship is self-evident, it is still a focus of research whether access to electricity causes economic development, or whether the contrary is true. Toman and Jemelkova (2002) start from the assumption that *ceteris paribus* an increment in any factor of production implies an increase in output, therefore assessing the disproportionate role of electricity access as a productivity-enhancing and development factor.[lxxxix] Contributing to this research, the Office of Technology Assessment (OFA) provided decades ago two different studies concerning the role of energy access on economic development, with specific attention to household labor time and how energy-inefficient human hand labor is relative to basic machines powered by an external energy source.[xc][xci] This produces extremely important spillover benefits, in particular for women and children that are now able to allocate the time spent on collecting traditional fuels, towards other income-earning activities or education (van de Walle et al. 2013, Bonan et al. 2016, OFA 1991).[xcii][xciii] Night-time illumination provides the possibility of better time allocation, which in turn improves different conditions like children's education.[xciv] Escribano et al. (2009) document the negative impacts that poor-quality electricity supply has on industrial productivity in different African countries, thus slowing the transition from agriculture-based to industrial-based economies.[xcv] Electricity access enables households to avoid thermal discomfort, with all the relative socio-economic and health implications that it comes with specifically in arid and tropical regions like sub-Saharan Africa, as clearly stated in Falchetta and Mistry (2021).[xcvi] Nevertheless, this is something usually overlooked during planning phases in developing countries, since new electrification programs tend to fail to meet projections of future demand. In their research, Falchetta and

Mistry provide evidence on how sub-Saharan countries have to keep into account thermal comfort needs in their projects of universal households' electrification. Failing to do so, might result in large energy-supply deficits and persistent energy poverty especially considering the increase between 1% and 8.7% in energy consumption due to projected warmer temperatures.

Although this topic remains under-researched, this may exponentially increase the probability of blackout and brownout events in hydropower-dependent countries, since high residential demand would coincide with low water levels in reservoirs, therefore reducing electricity generation. While access to electricity has a positive relationship with health improvements in populations, many scholars have already brought attention to the importance of reliable generation, since blackouts and load shedding events are responsible for producing negative consequences on human health. Irwin et al. (2020), gave much consideration to this theory, making impactful considerations over the necessity to improve the quality of electrification to pursue public health objectives.[xcvii] In the studies reviewed by Irwin and his colleagues, blackouts are generally associated with a reduced ability to deliver high-quality care to patients, but also a reduced ability of patients to access health care offered. Taking into account different factors like costs, institutional capacity, and overall demand, Cahil (2021) argued stand-alone or mini-grid power systems have been proposed in low-income rural areas, due to their relative reliability compared to national grids in least-developed countries(LDCs), in order to support the small healthcare facilities and the few basic electric appliances.[xcviii] Apart from reliability issues, during the last decades the deep interdependencies between energy access and health have been deeply studied, finding different positive health outcomes among which we find increased immunization (Chen, Chindarkar, & Xiao, 2016)[xcix], improved respiratory health (Accinelli, Lopez, and Aguirre, 2015)[c], and lower infant and maternal mortality (Wang, 2002)[ci]. The considerations around reliability in energy infrastructure are not limited to health issues. While quite dated, the landmark research by Schurr (1984) shows that the changes in the quality of energy services hold a solid potential to increase overall economic productivity, apart from the physical availability of energy per se.[cii] Although this concept is further developed in Toman and Jemelkova's work, they also raise attention on how energy infrastructure investments may compete with other development opportunities in the allocation of scarce capital in a context of poor policy planning and institutional resources. When considering poor rural households, the same dilemma over scarce resources applies. In order to achieve economic development in the context of rural poverty and inequality, Cook (2011) considers private and foreign investment in rural electrification as an important way to increase industrial productivity even in non-urban areas.[ciii] Concluding on this theme, in a policy brief provided by the Fondazione Eni Enrico Mattei, evidence is provided for the importance and necessity of a coherent top-down approach from developing countries governments, for the sake of efficient coordination between natural resources management, energy supply, and transportation, and consumers requirements.[civ] All in all, the positive interlinkages of electricity access with the numerous global issues discussed, understandably emphasize the need for universal electrification in the global fight to achieve better and more equitable living conditions for all humans.

1.6 Security Impacts of Large Dams Construction

With a general understanding of how increasing electricity generation may provide incredible benefits for the global population, the focus will now move towards the environmental, socio-economic, and political impacts of dam-building and hydropower generation. Hydropower plants all around the world generate more than 16% of the overall share of electricity consumed. Holding the lion's share of renewable energy capacity and being as aforementioned among the best technologies for preserving energy (pumped storage), hydropower plants are also the largest power stations for generating capacity (GERD, Three Gorges Dam, and Itaipu dam are the notable examples in Ethiopia, China, and Paraguay worth mentioning here). Nevertheless, construction takes a massive toll on the local ecosystem, with far-reaching consequences for downstream riparian countries, and with costs and negative impacts that are usually overlooked. According to the World Commission on Dams (2000), the construction and development of these structures resulted in a maximum of 80 million people being forcibly removed from their home ground and had negative effects on populations who based their lives off the nearby rivers.[cv] Richter et al. (2010) estimated that around 472 million river-dependent people living downstream dams were affected.[cvi] Dams have negative **impacts on ecosystems and the environment** in ways still poorly understood which lawmakers and decision-makers frequently leave unnoticed, for the greater good of socio-economic progress. Dam-building has cross-dimensional impacts overtime on different aspects of the river ecosystems on which it happens.

For what concerns the **political dimension**, dam-building is a practice capable of influencing the so-called sphere of "human security". While the term has no fixed accepted definition, its ambiguity is used to define security concerns that cover a wide range of issues, whether local or global, from economic threats to military insecurities (Paris, 2001).[cvii] Although vague, international relations scholars argue that this term is useful for non-state actors, such as non-governmental organizations (NGOs) in order to draw attention away from traditional state security concerns, and towards development, health, and environmental issues (Paris, 2001). Both Paris (2001) and Thomas and Towe (2002) suggest how human security as a term, is better suited to address transnational modern issues, therefore becoming appropriate in the context faced in this thesis, of transboundary water resources and dam-building.[cviii] Water is a necessary resource for different processes like food production, industry, transportation, recreation, municipal use, and delineation of borders (Veilleux, 2014).[cix] Considering the aforementioned vivid debate around natural resources and conflict, it must not surprise to find a similar number of discussions, trying to find connections between the environment and politics. While providing an extremely deterministic and debated perspective, Wittfogel (1957) argues the idea of a "hydraulic despotism" where governments hold power and legitimacy by controlling access to water through flood control and irrigation infrastructure.[cx] Wittfogel was among the earliest scholars to theorize the interlinkages between water and power dynamics, with many others following in his stead. Some examples are brought forward by Swyngedouw (1999; 1997) in the analysis of both Ecuadorean and Spanish waterscapes manipulation, which are linked to the ideological current of Spanish "Regeneracionismo".[cxi][cxii] In a later work, Kaika (2003) also seems to suggest a form of political power through the construction and control of critical water infrastructure.[cxiii] Daoudy (2020) identified the strategies of water weaponization with water infrastructure becoming both military tools (deliberate flooding and defensive fortifications), and instruments of "domination and legitimacy".[cxiv] Daoudy further elaborates the idea of "infrastructure power" theorized by Michael Mann (1984), according to which the state penetrates civil society by creating infrastructures that accentuate citizens' dependence on water systems.[cxv] Foreign relations are affected too, as Bakker (1999) underlines the importance of hydropower impacts on riparian countries, in the context of the geopolitical energy struggle of modernity.[cxvi] Some also provided hypothesis on how countries relying on hydropower, in their process of dam-building, may somewhat generate more internal and external conflict compared to their non-hydro power reliant peers (Gleick, 1993; Swain, 2001; Wolf, 2007)[cxvii][cxviii] In its historical perspective on the matter of inter-state and intra-state conflict due to water, Gleick and Heberger (2014) describe the dependency between "has and has-not" societal groups holding access to water resources.

According to a report made last year by UNDP (2020), human security is much more influenced by climate change than previously believed due to its aforementioned interlinkages with water, food, and energy systems.[cxix] Considering the aforementioned interlinkages between climate change and water, food, and energy systems, it comes as no surprise that extreme events like drought are increasing conflicts due to water scarcity and food insecurity. On another occasion, UNDP (2020) reported how different non-state armed groups are strengthened by environmental-driven scarcity and choose energy and water infrastructures like dam reservoirs as targets to seize and destroy.[cxx] The academic debate on human security in the context of water and energy infrastructures already investigated different socio-political dynamics generated by the development of infrastructures in transboundary rivers. Large conventional dams, in particular, are usually at the center of discussions around sovereignty limitations of other riparian states, something that becomes extremely important when focusing the attention on transnational basins (Wolf, 2007; Wolf et al., 2005; Sovacool and Walter, 2019).[cxxi][cxxii] Shared water systems end up becoming hotspots of political disputes and tensions, varying in intensity and risk as expressed by De Stefano et al. (2017) and Hirsch (2011).[cxxiii][cxxiv] In the specific context of sub-Saharan Africa, there is a material absence of technology, know-how, and funding to build and maintain water reservoirs. Consequently, local governments usually must rely on foreign banks and companies to create these crucial infrastructures. This situation of political vulnerability by foreign powers is embedded in the history of the African continent, for which an important reference is Rodney's and Shenton (1975), and Kalu (2015) studies.[cxxv][cxxvi] Different countries are usually involved in these bidding contracts, but the most academically interesting is China, which draws much attention due to the proportion of investments and their implications (McDonald et al., 2009).[cxxvii] Large-scale infrastructure in Africa usually entails direct provision of material, funding, training, and experts by China. Among others, Trofimov (2007) expressed how these practices entail security risks, [cxxviii] and how this kind of infrastructure lacking environmental and security reports, end up fueling neo-colonialist practices [cxxix] financial dependence which causes debt traps (Phillips, 2006)[cxxx] and institutional corruption due to lack of transparency (Moss et al., 2008; Odhiambo, 2008).[cxxxi][cxxxii] These practices are by no means specific to only Chinese state-owned and national firms, but Chinese state-owned firms are extremely important in the sub-Saharan dam-building boom, being the main developers and funders of these infrastructures. Foreign countries therefore finance and build environmentally and socially damaging infrastructures, which later on fuel inter-state and intra-state political tensions, as already happened on different occasions (Bosshard, 2011, 2013, 2016).[cxxxiii][cxxxiv][cxxxv] Hydroelectric power plants are also not inclusive and equal by nature.

Large dams have massive **social impacts**, due to the need to flood vast areas previously inhabited. The World Commission on Dams (2000) estimated how around 80 million have been displaced by dam construction (the majority of which in India and China).[cxxxvi] Displaced people are usually members of poor ethnical minorities (Schudder, 2008)[cxxxvii] which end up becoming the major risk-takers in this kind of development project. While framed as necessary for socio-economic development, dam-building causes further economic and cultural impoverishment for resettled populations, who have been rarely adequately compensated (Schudder, 2005; Brockerhoff and McDowell, 1998).[cxxxviii][cxxxix] Different examples provided by the academic community show how by interfering with local communities' livelihood, dams exacerbate poverty and economic inequality of marginalized and ethnic minorities (Wolf et al., 2005; Rothfelder, 2003).[cxl][cxli] Governments promote hydropower as a mechanism of economic development in rural areas, but in reality, these dams benefit industrial and urban centers hundreds of kilometers away (Magee, 2006; Bosshard, 2016).[cxlii] The academic literature on economic costs of hydropower externalities is both rich and diverse, with different scholars trying to quantify economic losses through environmental (Adams and Hugges, 1986; Holdren and Smith, 2000)[cxliii][cxliv], social (Cernea, 2004)[cxlv], health (Lerer and Schudder, 1999; Baird, 2011)[cxlvi][cxlvii], and economic impacts (Sovacool, 2008).[cxlviii] Concerning economic impacts, the aforementioned dependency on foreign funding and technology may have negative effects in economically frail nations, like sub-Saharan countries (Merrow, McDonnell, and Argüden, 1988).[cxlix] Some notable examples of mega-dams in fragile nations are Ethiopia with the Grand Ethiopian Renaissance Dam, with an estimated cost of more than 5% of its national GDP, and the Grand Inga Dam with a cost way superior to the national GDP (Green, Sovacool and

Hancock, 2015).[cl] While studies behind externality costs of energy production are still ongoing, there is empirical proof of the environmental impacts of damming a watercourse. Large dams may produce ecological degradation thousands of kilometers downstream due to the change they apply to the natural flow of a river (Flecker and Allan, 1993).[cli] Scholars studying the extent of the loss in biological diversity and ecological degradation due to dam-building produced a vivid scientific debate over the years, prompting for the protection of ecosystems that were not already artificially altered (Hughes and Noss, 1992; Karr et al., 1985; Brown et al, 2009).[clii][cliii][cliv] Poff et al (1997) provided a clearer depiction of how multiple habitats are present in rivers, and how human alteration of flow regimes "creating new conditions to which the native biota may be poorly adapted".[clv] As dams are important for food security due to irrigation and flood control, there is widespread evidence of how bad river management and artificial alterations may consistently damage the livelihood of downstream fisheries and local dwellers that rely on the basins food production (Ziv et al., 2012; Baird et al., 2005).[clvi][clvii] Overall, preliminary studies on environmental impacts of large dams are not extremely reliable, as these are commonly made on a site-based perspective, and not on a basin-wide analysis, which is the scale that receives negative outcomes.[clviii] In the continuous flow of dammed rivers, not only biodiversity but also sediment transport creates risks (Poff et al., 1997). Different scholars reported the danger created by limiting sediment transfer, which would cause coastal erosion in the rivers delta, on top of further disrupting river hydrology by facilitating deforestation and loss of biodiversity (Anthony et al., 2015).[clix] Some positive examples of partial restoration have already been shown, but in order to completely understand the possible impacts of dams on the basin's ecosystems, further studies are still required (Baird and Quastel, 2015).[clx] According to Arthington (2012), by releasing specific amounts of the water held in reservoirs, it should be possible to imitate the natural flow of the river and restore some of the ecosystem functions.[clxi] Unfortunately, this also entails economic and efficiency loss for the company operating the dam. While still far from reaching a balance between economic efficiency and negative ecological effects, at least two different studies from Kennedy et al (2016)[clxii] and Schmitt et al (2019)[clxiii], seem to suggest that dams built-in specific ecosystems may still be extremely profitable, with limited impacts on the overall basin ecosystem. Conclusively, while the impacts and dangers around dam-building seem to paint a grim picture around this technology, benefits provided by creating water and energy access are usually harder to estimate. In light of all the scientific and academic evidence presented, some considerations must be made. Dam reservoirs are important not only for their potential socio-economic benefits but also for the vulnerabilities they create. Our warming climate gives every form of renewable energy an important role in the decarbonization of national economies, and this is particularly true for hydroelectricity due to its strategic advantages. However, the necessity for carbon-free energy must not overshadow the sensible risks and drawbacks underlined by the literature provided (Sovacool and Walter, 2019; Koch, 2002).[clxiv][clxv] These benefits and impacts are local, in the case of small reservoirs, but may also become national and international in the case of the large reservoirs on transnational basins. A prominent example of international impacts in the case of sub-Saharan Africa is that of the Grand Renaissance Ethiopian Dam (GERD). While promoted domestically as a great development project, the local population in the proximity of the dam has already been damaged. But the most important negative impact is probably the political one, with the grave tension created between Ethiopia and Egypt. Diplomatic talks are still in place but considering the citation from Boutrous Boutrous-Ghali at the beginning of this work, it is noteworthy to ask whether certain large infrastructures are actually worth the risk, and what will the future of hydropolitics reserve in the context of climate change.

2. Climate, Water, and Energy Systems in sub-Saharan Africa

“*The next war in our region will be over the waters of the Nile, not politics***”**

Boutros Boutros-Ghali, 1988

2.1 Electricity access and generation in sub-Saharan Africa

The relationship between energy and society has been a for decades an abundantly researched and discussed topic. This discussion is usually approached in the context of developing countries, researching the causes and implications of energy poverty. This is a frequent condition in sub-Saharan Africa, which defines both domestic fuel for cooking and low or lacking electricity consumption. While different definitions are used in the academic research, this thesis will use the International Energy Agency (IEA) definition of access to electricity as follows:

“*a household having reliable and affordable access to both clean cooking facilities and to electricity, which is enough to supply a basic bundle of energy services initially, and then an increasing level of electricity over time to reach the regional average*”.[clxvi]

Following this definition, energy poverty at the global level has been progressively reduced during the last decades, with the number of people living without access to electricity dropping from 1.2 billion to 759 million people globally between 2010 and 2019.[clxvii] Although figures vary among each country, the distribution of electricity access is not exempt from inequality issues, with a sensible discrepancy in grid connections between populations in urban and rural areas. While investments and solutions are being sought to provide access to national grids in rural areas, the objective of universal electrification is far from being accomplished. Chapter I summarized the main linkages between electrification and economic growth, thus implicitly asserting how energy poverty represents an important obstacle for sensible socio-economic improvement in sub-Saharan Africa. Nevertheless, in the wake of the global effort against climate change, different international funding institutions are focusing their investments in developing countries towards green and sustainable infrastructural projects (see the Green Bonds from the World Bank for a clear example).[clxviii] Global institutions linked to the United Nations approached the problem of energy poverty in the context of climate change, by creating a list of objectives famously known as the *Sustainable Development Goals* (UN SDGs). These SDGs represent a collection of 17 global goals to "*achieve a better and more sustainable future for all"*.[clxix] The creation of these objectives sparked a vivid debate in the scientific community, in particular as SDGs are functional as a primary benchmark to assess improvements or worsening of certain human conditions throughout the world.[clxx] Among the most discussed, the SDG 7 has the objective to provide *reliable, clean, and cheap energy for everyone,* and while other SDGs are interlinked among each other, SDG 7 exerts a strong influence on almost every other goal among which SDG 1 (Poverty Eradication), SDG 2 (Food Security), SDG 3 (Health), SDG 4 (Education), SDG 5 (Gender Equality), SDG 6 (Clean Water), SDG 8 (Jobs), SDG 9 (Transport), SDG 11 (Sustainable cities), SDG 13 (Adaptation to climate change).[clxxi] [clxxii] Thus, while providing universal access to electricity is framed as a common challenge by international institutions, tackling the issue of energy poverty must keep into consideration both socio-economic considerations and environmental sustainability. Much of the global energy generation is still over-reliant on fossil fuels, and the "modern standards" of consumption in developing and developed countries are unquestionably linked to anthropogenic climate change. Climate warming is recognized as one of the biggest challenges and future uncertainties on the global level faced by the common human society, which is demonstrated by the growing socio-political attention that this phenomenon is receiving in the international arena, and how energy investment is more and more focused on substituting older polluting fossil fuel plants with clean and renewable means(IPCC, 2021; European Commission, 2019).[clxxiii] The interconnectedness of energy consumption and socio-economic well-being is a clear reason to combat energy poverty but doing so in the "traditional way" results in potentially more dangerous for environmental and health conditions. In fact, the pattern followed by major developed countries and other developing countries such as China and India would prove extremely dangerous for millions of people due to worsening health or extreme climate conditions. The important (but not exclusive) relation between a warming climate and greenhouse gas emissions (GHG henceforth) creates a compelling need to find a way to fuel sub-Saharan Africa without creating polluting emissions through fossil fuels combustion. Energy is directly related to 73.2% of overall GHG emissions, with electricity and heat production holding the lion share of total carbon dioxide equivalent (CO2E) at 15.01 billion tonnes of overall 49.4 billion tonnes produced respectively in 2016.[clxxiv]

Global awareness towards climate change led to increased investments towards technological research of new renewable and sustainable generation means, which may preserve the consumption patterns of modern industrial societies without causing the environmental degradation experienced until now. Overall, power generation is still overly dependent on fossil fuels, which claims 63% of the overall production with slightly over 17,000 TWh produced in 2019, but in the last few years, renewable energy generation plants have become extremely competitive with the previously unchallenged coal and oil plants, testified by the growing share of renewable in the global energy mix.[clxxv] As sub-Saharan African national governments and policy-makers attempt to answer the problem of widespread energy poverty, global institutions try to simplify access to 'green funds' in order to avoid additional GHG emissions, but also to avoid the health problems and environmental degradation linked to fossil fuels consumption, which creates obstacles for social and economic progress in the long-run.[clxxvi] According to the World Bank database, sub-Saharan Africa generates 3% of the global energy production and remains a small contributor to the world's total CO2 emissions due to the currently small economic and industrial activity and the lack of universal access, with an estimated 2,42% of global emissions and 823.424 Kt of CO2 produced in 2018 (International Energy Outlook, 2020).[clxxvii] If the current patterns are not interrupted by major events (such as the Covid-19 pandemic), sub-Saharan Africa is expected to undergo visible rapid population and economic growth, which will likely result in quintuple energy consumption from 117 TWh in 2019 of installed capacity, to 577 TWh in 2050. By 2050, global energy use is expected to increase by 50% mostly as a result of non-OECD population and economic growth, with sub-Saharan Africa and Asia as the main drivers of this electrification process (US Energy Information Administration 2014).[clxxviii] The electrification investment in the region unfortunately has barely kept pace with the rapid population growth. Recent future projections have estimated a sensible increase in the sub-Saharan African population, growing from today's 1.34 billion people to an expected 4.28 billion people by 2100.[clxxix] These figures underline a once-in-a-lifetime occasion for developing countries to create sustainable socio-economic growth in curbing economic inequality and have access to better living conditions for all, but may also backfire in greater inequality and environmental degradation depending on different situations. Electricity access will provide all the benefits briefly described in the literary review offered in chapter II. However, the situation reveals to be extremely complicated and policymakers must keep into account different aspects, such as technological specificities of each generating means, the cost-effectiveness of electricity generation, and finally the region-specific natural resources endowment.

Untapping the renewable generation potential in the sub-Saharan African region holds the key towards ending energy poverty and supporting economic growth and social well-being in the continent with as little environmental degradation as possible. Sub-Saharan Africa hosts vast amounts of both renewable and non-renewable resources which have been recently discovered and will be tapped onto to achieve universal electrification. Due to the magnitude of geographic distances taken into consideration, it does not come as a surprise that SSA's resource endowment is extremely diverse and uneven throughout the continent. Fossil fuels are concentrated in specific clusters in Western, Central, and Southern Africa, with Eastern Africa presenting modest resources. Notable exploitable uranium reserves are present in Namibia, Niger, South Africa, with Zambia and Botswana holding sufficient amounts of cost-effective reserves.[clxxx] Due to a large part of its landmass being located near the equator, SSA is also exposed to a strong amount of sunlight year-round, holding a theoretical capacity potential of 660.000 TWh per year of solar energy, with East and Southern Africa identified as having the highest potential.[clxxxi] Concentrating Solar Power (CSP) also showed promising potential as being around 470.000 TWh/year, with Southern Africa and Eastern Africa demonstrating the highest potential. According to statistics from IEA however, only 5.2 TWh of solar PV and CSP were developed and exploited in the continent.[clxxxii] Geothermal is also present mainly in the eastern part of Africa, with a potential of more than *15 GW (*Geothermal Energy Association, 2019). Among these untapped resources that will power Africa in the future, the academic and political discussion is focused on hydropower. While uneven in the presence and exploitable quantity, hydropower remains the primary renewable resource in sub-Saharan Africa, with over 132 TWh of electricity production in 2020, accounting for an overall 16% of the total share.[clxxxiii] Nevertheless, the gross techno-economically feasible untapped potential is estimated at 2.9 PWh/year below a cost of $0.09/kWh (Zhou et al., 2015), with most of its potential localized around its major river basins (Congo, Nile, Senegal, Niger, Zambesi, Volta, Orange) where 40% of the hydro-electrical potential can be found in the Congo basin alone. While most of the potential is found in Central Africa, noteworthy estimates are also found in Southern, Eastern, and Western Africa. With the more or less constant growth in installed capacity, by 2030 it is expected to overtake coal as the highest share of power production in the continent (International Energy Agency, 2017).[clxxxiv] Despite the renewable nature of hydroelectricity, this technology also comes along with severe social and ecological adverse effects, e.g. relocation of people and transboundary conflicts, fragmentation of free-flowing rivers, and habitat changes, thus further threatening freshwater biodiversity (Zarfl et al., 2015).[clxxxv] Finally, according to the Rio+20 targets, countries are required to meet their growing energy demand through the use of Kyoto-compliant energetical resources. This may provide a justification for the increase in investment in hydropower during the last decade compared to the relative stagnation in construction. Since 2011, global hydropower electricity capacity is expected to grow from 980 GW to 1,700 within 10-20 years. This global boom in dam construction led to around 2 trillion US$ being invested in the last decade towards planned or under construction dams. Africa is the main recipient of financial investment and general capacity addition in hydropower, in part due to its extremely low exploited generation potential (around 8%) (Zarfl et al., 2015). Africa has been historically plagued by energy poverty, and this increase in generation capacity from hydropower may provide important social and economic potential improvements which have yet to be deeply investigated by academic researchers (Andersen and Dalgaard, 2013).[clxxxvi] However, energy policymakers must be aware of a wide array of negative effects and risks that determines hydropower generation and overreliance on it in their energy mix. A limited adaptive capacity, the scarcely diversified energy mix, and lack of backup options represent important weaknesses of the sub-Saharan countries' energy provision.[clxxxvii] A high level of dependency on hydropower, therefore, makes a country specifically prone to supply disruption in case of drought-like climatic conditions (Farquharson et al, 2018).[clxxxviii] These outages have far-reaching implications on different aspects of countries' productivity and economy (Cole et al, 2018; Andersen and Dalgaard, 2013).[clxxxixcxc]

2.2 Climate change and the Water-Energy system in sub-Saharan Africa

Recent decades saw the effort of the global research community, in investigating the linkages between our climate and water, food, and energy resources. While water is a primary input of food production, due to this thesis being focused on electricity production by hydropower plants, a conscious choice is made to exclude food scarcity from climate change from this small review Further considerations on the latter subject are found in the Geoglam monthly reports, produced with data collected from satellite observations,[cxci] and other papers like Armah et al(2011)[cxcii], and Kogan et al (2019).[cxciii] Thus, with the scientific evidence provided until now, it is possible to see the nexus between water and energy as extremely complex and intricate. Placed in the context of climate change, the water-energy nexus is subject to impacts with enormous repercussions on every human system. The IPCC (2013) has been providing scientific evidence of climate change and its physical impacts for decades now.[cxciv] In this report, data evidence is provided asserting how extreme weather conditions, including heatwaves, droughts, and floods, will become more frequent and intense (IPCC, 2021). The impact of these phenomena will have different effects in different regions of the world. A recent World Bank report (2021) stated how the African climate is warming at a faster rate compared to the rest of the world. The widespread increase in frequency and intensity of heatwaves and more erratic precipitations are worsened by a general scarcity of adaptation measures in the continent. Apart from providing further proof of the positive relation between climate change and conflict, Couttennier and Soubeyran (2010) using the Palmer Severity Drought Index (PSDI) confirm an overall increase in drought events and severity in sub-Saharan Africa compared to the rest of the world.[cxcv] Both the World Bank reports from 2021 and 1998 suggest the particular vulnerability of the continent compared to other regions of the world, due to economic (overreliance on agriculture, low income, low investment in water infrastructures) and social conditions (ethnic fractionalization, low institutional capacity).[cxcvi] In both reports, hydropower plants fall in the category of water infrastructures that increase developing nations' adaptation capacity to withstand heatwaves and long-lasting droughts. Nevertheless, there is a growing understanding in the scientific community regarding the impacts of climate change on water resources and electricity production in large dams for hydroelectric purposes.[cxcvii] Consistent studies on the different scales have been conducted, evaluating the potential impacts of our warming climate on national and transboundary rivers. Following is a list of some selected academic findings of the geographic areas of interest to this thesis.

Southern Africa has more arid areas compared to the other relevant geographic areas considered in this thesis. An assessment made by de Wit and Stankiewicz (2006) on the relationship between rainfall and river discharge across Africa, found that a -10% decrease in precipitation would decrease surface drainage by -17%. The figure raises to a -50% decrease in case of reduced rainfall. Due to the relatively arid climate, Southern Africa's future is expected to be more prone to drought events due to lesser rainfall, with an estimated decrease between -10 and -20% in river discharge. Similar expectations are made in Faramarzi et al (2013), estimating particular repercussions for water resources in the area (while estimating increased rainfall in Central and Eastern Africa).[cxcviii] In a case study over the Zambezi basin, Kling et al (2014) assess the watercourse conditions under different scenarios.[cxcix] When examining the water discharge, the presence of three large hydropower plants and the strong evapotranspiration produce large impacts on the basin runoff. Creating a time-series of precipitations and temperature in different levels of the basins, they conclude how runoff is more sensible to change in precipitation rather than temperature. Accounting for future increases in water withdrawals for irrigation purposes, agricultural expansion is seen as having a similar impact on the river flow to a possible temperature increase of +4°C. In a successive study, Kling et al (2015) witness significant uncertainty in precipitation frequency, which would considerably reduce annual discharge, which could cause an important reduction in electricity generation.[cc] Spalding-Fecher et al (2016) in a specific focus on the expected irrigation development, found a strong possibility of inter-operational competition along the river, between water extraction for agriculture and water consumption for hydroelectric generation. This would create lower efficiency and limited cost-effectiveness, compared to the expected levels in the respective feasibility studies of each dam.

Due to the widespread lack of electricity access in sub-Saharan countries, the objectives of expanding generation capacity and increased access largely rely on hydropower due to both low costs and reliability. In Kammen et al (2015) is conducted an assessment on the situation of energy poverty in the Eastern Africa region, where hydropower is the dominant form of capacity addition.[cci] In the study, inherent risks around such overreliance are discussed, with considerations on possible cost overruns which may prove electrification a costly ordeal for the low-income population of East Africa. However, the situation may aggravate not only due to underestimation of projects costs and climate change but also due to increased competition with other water uses. Holman et al (2016) provide evidence of the necessity to account for economic growth and agricultural expansion in climate change modeling studies related to water inputs.[ccii] This lack of considerations during energy infrastructure planning could counter-intuitive harmful effects which could spill over to other countries with grave political repercussions (Arjoon et al, 2014).[cciii] Accounting for future climatic conditions is necessary for the energetical development of this region. Sridharan et al (2019) developed a framework by soft-linking long-term electricity expansion models for the EAPP (Eastern African Power Pool).[cciv] They call for stronger cooperation in the EAPP area to address the vulnerability of hydropower dependency in a climate change context, in order to facilitate the cross-national transfer of energy, improve reliability, and keep costs low. They also explain the advantages provided by hydropower to adapt to the future increased tendency to flood events, predicted by Shongwe et al (2008)[ccv] for the Eastern part of Africa. Shongwe and colleagues predict an increase in interannual variability of precipitation and an overall wetter climate but expect higher temperatures that will reduce the streamflows and water levels. Reliability created by stronger cooperation may have limited effects in improving energy supply, since in Conway et al (2017) the predicted supply disruptions may be worse than expected.[ccvi] The major African rivers, which also represent the main suppliers of hydropower electricity for sub-Saharan countries, are all transboundary. Both the Zambezi and Nile basins host hydroelectric plants that supply different countries, which in Conway and colleagues opinion create inter-regional clusters, therefore subject to concurrent reductions in generation across the same river basins. This cluster-scarcity tendency is recognized in other works (Spalding-Fecher et al, 2017; Hellmuth et al, 2017).[ccvii] [ccviii] Nevertheless, Conway and colleagues propose to intensify cooperation across central, eastern, and southern power plants, since they find little correlation between scarcity in Congo, Zambezi, and Nile River, thus enabling reliable electricity supply through energy trading.

All in all, the amount of literature around the relationship between disruption in hydroelectricity generation and the forecasted increase in drought events caused by climate change provide compelling evidence, with numerous nation-specific case studies with important examples in Brazil (De Jong et al, 2018),[ccix] Portugal (Teotonio, 2016),[ccx] Finland (Kuusisto),[ccxi] and Italy (Majone, 2016).[ccxii] These different perspectives seem to decisively point towards a clear correlation of dry or wet events (Seljom, 2011; increase in efficiency is expected in Norway) [ccxiii] and a general increase in heatwaves, reducing water availability globally (Hamududu and Killingtveit, 2012; Van Vliet et al, 2016a and 2016b; Hoes et al, 2017).[ccxiv][ccxv][ccxvi][ccxvii] Water scarcity threatens energy security also in mid-high income countries, which have a higher share of thermoelectricity generation in their national energy mix. In Van Vliet et al (2012), heatwaves during summer periods are bound to have consistent effects in both hydropower and thermoelectric generation due to water scarcity, causing reduced efficiency and electricity supply during periods of thermal discomfort when energy request may actually be higher. [ccxviii] Extremely similar results are found in the works of Rubbelke and Vögele (2011),[ccxix] and van Vliet et al (2016).[ccxx] While only Southern Africa is considered in the latter study, drought years see an average reduction of 5.2 – 6.6% in hydropower utilization rates, and 3.8 – 9% in thermoelectric rates based on the intensity of the heatwave observed. Besides witnessing the highest interannual variability in utilization rates of hydropower, Southern Africa experiences also the largest heatwaves of the observed geographic samples. Be that as it may, the amount of scientific evidence provided by the academic literature may potentially account for crucial components of the energy development strategy of the sub-Saharan community. The observations and forecasts provided concerning climate change and the subsequent inter-annual variations in precipitation and river discharge, constitute visible threats towards the energy security of these low-income nations, with complex impacts on different aspects.

Climate change is expected to affect the global and regional hydrological cycles. Warming temperatures will enhance evaporation in water bodies (1999), [ccxxi] and this will increase the water-holding capacity of the atmosphere, increasing precipitation frequency and stronger rainfall events. Consequently, it follows how the naturally occurring droughts in a normal hydrological cycle, are likely to be intensified in frequency and intensity due to enhanced evaporation. However, the consequential increase in precipitation is not locally bounded, thus incrementing rainfall events, intensity, and risk of flood events in other regions of the world.[ccxxii] Relations between these meteorological events are not yet understood completely, however different global climate models tried to represent the intensification of these events on the continental and global scales under different projected climatic scenarios (Dai, 2011; Sheffield and Wood, 2008).[ccxxiii][ccxxiv] Notwithstanding the different impacts that climate change will have on the global scale, this will result in very serious implications for some regions of the world. Prudhomme and her colleagues (2014) provided a multimodel experiment, identifying hotspots of future droughts where water resource management aimed at ensuring water security in a changing climate.[ccxxv] Due to climate change, rainfall patterns are bound to grow more and more erratic in the future. This phenomenon is not bound to happen regionally and will result in a climatic change on a global scale. This places countries with scarce institutional capacity in a tight spot. Sub-Saharan countries are largely dependent on these rainfall patterns. According to the International Water Management Institute (IWMI, 2009), more than 95% of the farmed land in this continent depends on rainfed agriculture.[ccxxvi] The amount of crop produced per drop of water in rainfed farming tends to be extremely low. Lacking efficient water infrastructure, losses from evaporation are high. Figure 2 provides a visual representation of how much variety in intra-regional rainfall there is across the sub-Saharan region for each country described. Considering the aforementioned vulnerability from water scarcity of the African food production, Figure 2 shows how much rainfall variation exists in the geographic territories selected. Considering the literature provided up to this point, the vulnerability produced by water scarcity is not limited to food production but also comprehends energy generation, river ecosystems, human livelihood, and municipal use. While some countries are generally drier, like Namibia and Sudan, and others are clearly wetter, like the Republic of Congo and the DRC, some countries show notable variability between wet and dry areas in their territories, as seen in Ethiopia, Mozambique, and Tanzania. In Chapter IV, these countries show a statistically significant correlation between drought events and reduced hydropower generation, thus providing some confirmation on how water scarcity and energy generation are actually intrinsically linked, particularly so in this region.

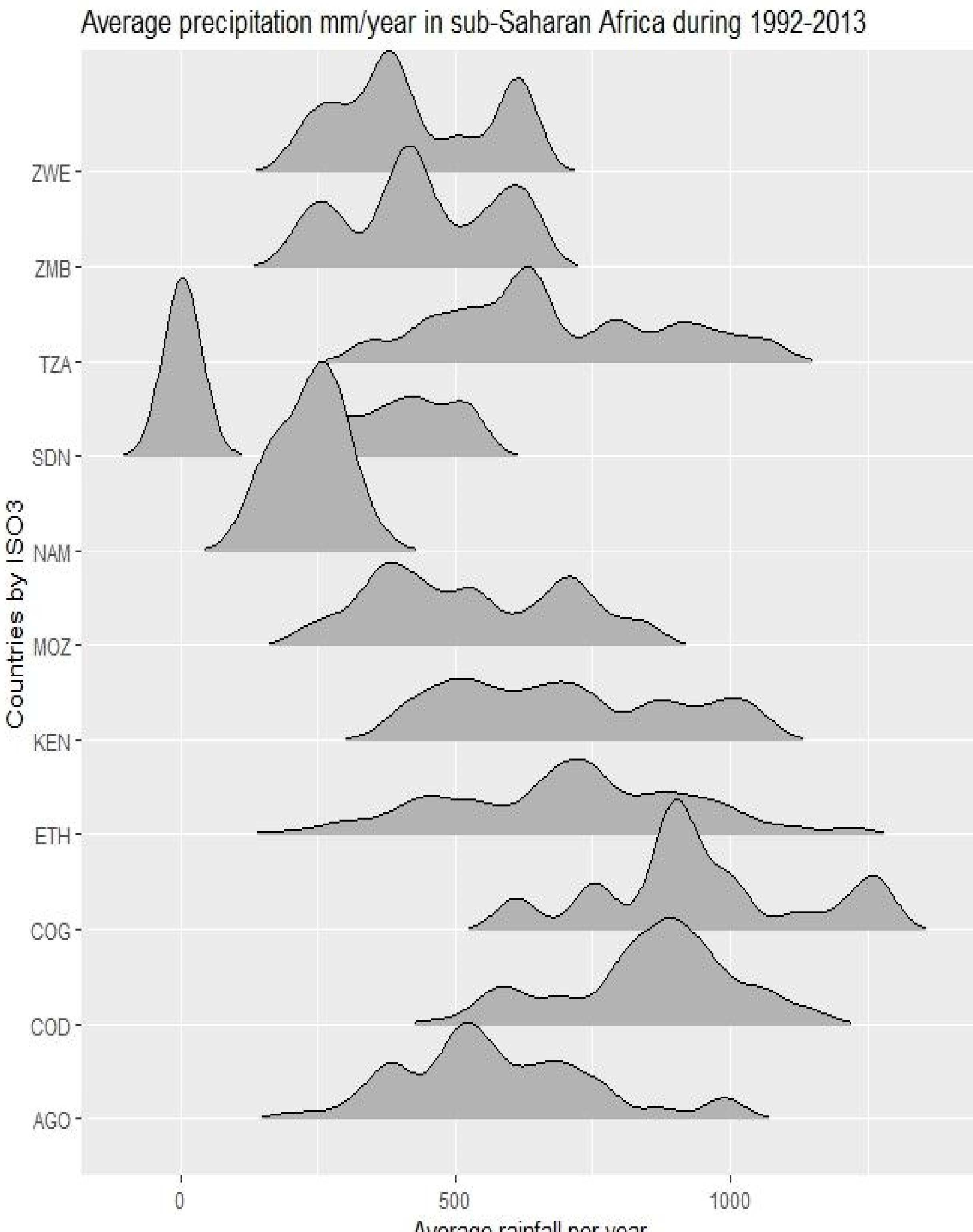


Figure 2*: Distribution of the average precipitation levels in mm/months of rain between 1992-*

2013 in the selected countries. Source: Own elaboration based on the CRU precipitation data.[ccxxvii]

In this region, land for agricultural use is increasingly degraded and crops production is particularly vulnerable to drought or floods events. Being situated in an intertropical area, the continent is subject to high average temperatures and high precipitation levels. Nevertheless, these high precipitation levels are not equally distributed either geographically, or temporally. During the year, climate alternates between wet and dry seasons and overall high temperatures, with Eastern Africa becoming gradually drier moving towards the Horn of Africa arid region. Precipitations in Eastern Africa have a strong seasonal character, which often leads to extreme precipitation events of droughts and floods. The fifth assessment report made by the IPCC (IPCC, 2014) details an overall increase in intensity for wet and dry periods in Eastern Africa, with areas subject to floods increasing the probability of floods and vice versa.[ccxxviii] Overall, the projections made in the IPCC report indicate an increase in extreme wet days by the mid-21th century in Eastern Africa. While uncertainty over climatic projection models is still present, climatologists seem to indicate how this increase will not be distributed during the year but will simply make already rainy seasons wetter.

Thus, while future projections point towards an overall increase in rain levels, this will not provide any benefits to rainfed agriculture. Although somewhat dated, in his study Glantz (1992) discusses the importance of temperature changes. In particular, he notes the indirect role that temperature plays on evaporation rates and hence water availability, particularly in areas where there is a delicate balance between evaporation and precipitation (Glantz, 1992).[ccxxix] Warmer average temperatures expected in the future, combined with more erratic, extreme, and less predictable rainfall patterns, make African agriculture even more vulnerable. According to Li et al (2016), five of the seven most flood-prone countries are located in East Africa (Ethiopia, Sudan, Tanzania, Kenya, Somalia). Flood and drought impacts on mortality, income, and other socio-economic aspects have already been explored in the literary review offered in Chapter I, but an overall reference of the region-specific impacts in Africa can also be found in Di Baldassarre et al (2010).[ccxxx] These future trends are still moderately speculative since many of these projections depend on how much emissions will present-day nations actually curb. With his work, Downing and his colleagues (1997) also seemingly reject deterministic views. They note how, while warming and drying trends in Africa persist and will grow worse, development practices in these countries will bolster the adaptation and mitigation capacity.[ccxxxi] The collective conclusion of the author in this last paragraph, is that food insecurity and poverty determined by the future impacts of climate change, strictly depend on how the developing nations adapt and improve their water management and infrastructure.

The structural climatic and hydrological conditions in sub-Saharan Africa are, per se, not particularly fit for water-dependent agricultural practices. As witnessed, rainfed agriculture is by far the most prevalent type of farming in this region with 95% of the land produced with little to no irrigation infrastructure. The same report from the IWMI (2009)[ccxxxii] suggests how poor income, water scarcity, and hunger are closely interlinked problems. One in five harvests in sub-Saharan Africa are claimed by drought events and leaving aside productive issues, malnutrition and poverty are increased in a continent highly reliant on subsistence farming for income and food security (Kijne, Barker, and Molden, 2003).[ccxxxiii] Much of the rain that does fall is lost through drainage, surface runoff, and non-productive evaporation due to the lack of water infrastructure in developing countries. Putting these considerations in the perspective of the aforementioned change in climatic conditions over the continent, the situation for sub-Saharan agriculture and the high share of the population that relies on it is bound to progressively worsen in the next years. Thus, the present and future climatic trends bring further evidence on the important role that efficient water management techniques and infrastructures are bound to cover in the future of developing countries. According to the assessment made by Wani, Rockström, and Owesi (2009),[ccxxxiv] investing in supplemental and small-scale irrigation creates opportunities to finally manage in an effective way rainwater and soil moisture. Enhanced security for their harvests consequently gives farmers the means to invest their small surplus, in other productivity-boosting technologies, such as fertilizers and high-yielding seed varieties, that would consequently boost agriculture efficiency even more. Different researchers support the idea of a "spill-over" thesis proposed by Wani and colleagues, where a small efficiency-improving input may generate progressive benefits in productivity, income levels, food security, and water security. The general belief is that by granting reliable access to water and increasing efficiency, farmers would be able to grow secondary lucrative crops, thus generating more income and food security (IWMI, 2010).[ccxxxv]

Rural populations are usually more vulnerable to climate change, due to their reliance on agricultural income and lack of adaptive capacity. While considering the energy sector in sub-Saharan Africa, it is worthwhile to mention the challenge of providing reliable electrification in rural communities. Extending grid connections to rural areas usually necessitates high costs, with limited returns, thus pushing decision-makers to favor large and centralized power plants with higher cost-efficiency, in the rolling out of electrification programs. Studies conducted on the theme of rural electrification in Africa underline how grid electrification in rural areas poses different economic and technical challenges. Lenz and her colleagues (2017) underwent a study about the effects of the Rwandan Electricity Access Roll-Out Program (EARP) on Rwandan households.[ccxxxvi] Their main conclusion was that most of the rural and urban households with the opportunities to access the electrical grid were in fact connected. Nevertheless, consumption levels remained low and no visible increase in productivity from electricity use was observed. Other scholars somewhat confirmed these results concerning grid extension. In Chaplin et al., (2017), a research team conducted a large-scale evaluation of the rural electrification program in Tanzania.[ccxxxvii] Along with some obvious positive relation with social welfare, they witness no increase in non-agricultural income or productivity. Finally, Lee et al., (2016) provide evidence from the grid extension in rural Kenya. In their findings, connecting rural households provides doubtful economic and productive returns, underlining how social returns may be higher by investing in other sectors like transportation, education, and health.[ccxxxviii] The last decades witnessed an important increase in solar panel efficiency. This enabled different Non-Governmental Organizations (NGOs) to provide household-level electrification programs in rural areas where poverty and high distance would not enable grid connection. Some of these small and micro-scale electrification programs caught the attention of private and institutional investors. A variety of scholars underlined how off-grid small-scale power generating technologies are increasingly cost-efficient and economically competitive compared to large-scale grid-connected power plants. Solar PV is still somewhat limited by reliability and energy-storage issues that limit its supply efficiency. Kougias et al., (2016) instead proposed a model of energy system optimization by combining small-hydropower plants and solar PV systems, thus answering the underlying issues of both technologies with their complementarity.[ccxxxix] Other recent case studies geographically centered on sub-Saharan Africa emphasized the importance of small and micro-scale hydropower, as a cost-efficient and reliable pathway to rural electrification (Kaunda, Kimambo, and Nielsen, 2012; Ebhota and Inambao, 2017; Ahlborg and Sjöstedt, 2015).[ccxl] [ccxli] [ccxlii] Nevertheless, large-scale centralized power plants and grid extension still receive the majority of funding due to higher economic returns for private investment, and socio-economic improvements among the population for political institutions.

2.3 Dam-building and decision-making

Climate change, water scarcity, and the relative food insecurity so created have all become mainstream topics in the academic debate that concerns the sub-Saharan African region. Different attempts at modeling the interlinkages of these global challenges have been made, and the analysis of positive relations with other socio-economic and political aspects successfully produced results, although the measure of how much these influences are still debated. The importance of managing water resources has been highlighted not only in dry regions but also in regions usually subject to a wet climate. This is motivated by the high evaporation and soil conditions tropical countries are usually subject to (Chambers and Roberts, 2014).[ccxliii] Sub-Saharan Africa is a particular geographic region where water scarcity is conditioned by the unequal distribution of intra-seasonal rainfall, and where electricity generation capacity still trails behind economic and population growth. Thus, decision-makers in Africa decide to push the investment funds and state capacity they possess towards answering these water-energy scarcity problems. While RoR plants provide electricity generation at small environmental and social costs in comparison to other technologies, usually decision-makers give priority to the development of large conventional dams. Floods and droughts represent respectively 43% and 5% of natural disasters, which produce an important impact on water resources. The average annual economic damage caused by droughts is calculated at $5.4 billion and that of floods at $31.4 billion. Furthermore, agriculture in developing countries is usually rainfed as previously discussed, thus extremely dependent on water inputs. In a context of a booming population, all kinds of water consumption, whether municipal, industrial, or agricultural, are destined to see their demand increase. In this unique context, conventional dams provide enormous advantages.

The new generating capacity added grants relatively stable and constant energy for the national grid at a cheap price. Moreover, conventional dams are frequently multipurpose, consequently capable of increasing water capacity in a sensible way, which has spillover benefits on agriculture and municipal needs. Finally, these structures provide flood-control and mitigating effects on droughts if correctly managed. While the risks connected to these projects have been already discussed dams in the literary review section (see Chapter 1), policy-makers in countries plagued by budget constraints and poor infrastructure see obvious benefits from the consistent multiple benefits that dams grant to the water and energy sector. Overall, sub-Saharan Africa witnessed a strong modernization of the regulatory framework for private energy firms, since to achieve universal electrification public funding is not enough.[ccxliv] This provided access to large amounts of investment from different foreign institutional sources. Foreign investments have growingly focused on off-grid resources, increasing electricity access in rural areas where providing access to the national grid would prove to be too costly. Nevertheless, public funding continued adding capacity and much of the focus from policymakers has been on hydropower. Hydroelectricity ranges from 99% of overall energy production in the Democratic Republic of Congo, to 33% in Tanzania. Figure 3 shows the largest 10 dams in sub-Saharan Africa. The figures in the pie chart represent the MWh produced as reported in the Global Power Plant Database (WRI, 2018).[ccxlv] These 10 dams have an estimated generation capacity of 8240 MWh, accounting for 67% of the overall energy produced by the 40 power plants taken into consideration in **Table 2** (Chapter 3).

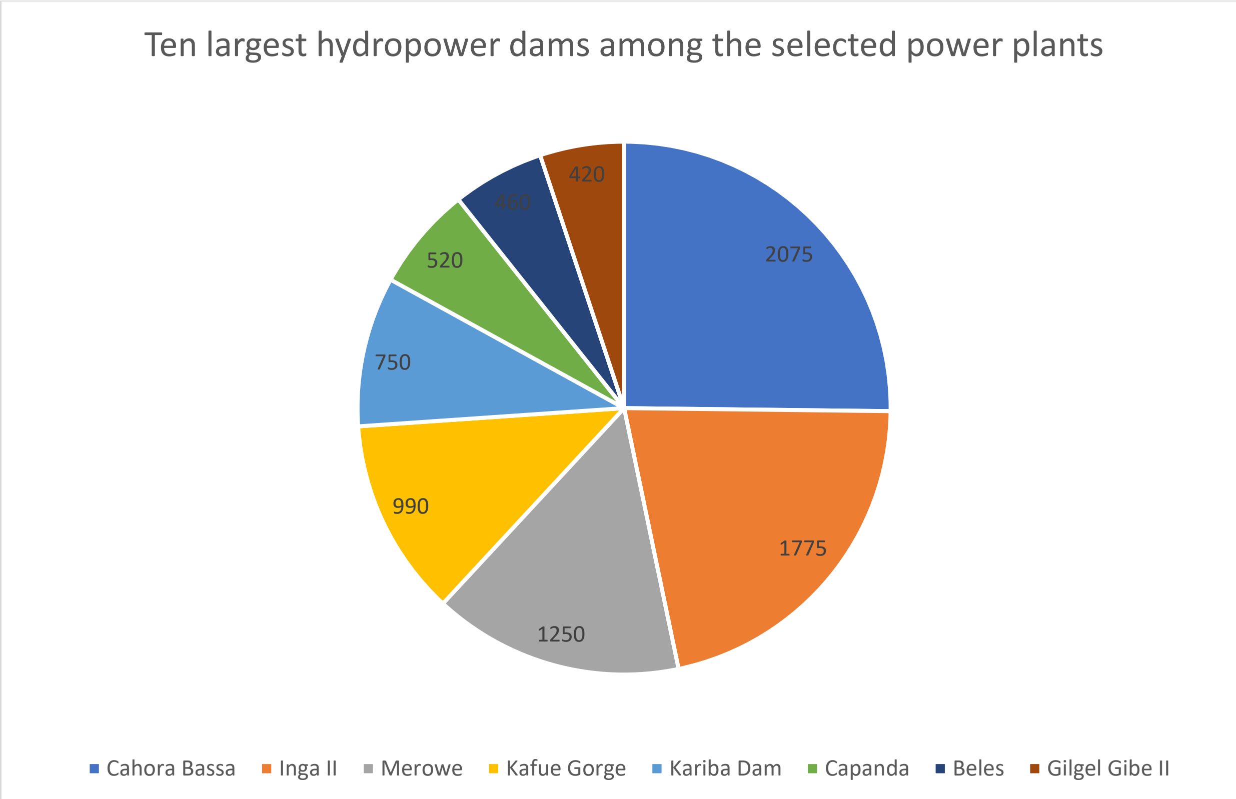


Figure 3*: Pie chart of the ten largest dams in the sub-Saharan region. Values inside the chart represent the installed capacity of each power plant in MW. Source: ICOLD and GRanD database.*[ccxlvi]

A vast academic literature has been produced concerning universal electrification, especially in the context of the Sustainable Development Goals (SDGs) (Nerini et al, 2018; IREA, 2017; Waage et al; 2015).[ccxlvii][ccxlviii][ccxlix] Among these global goals, SDG 7.1.1 (concerned with granting clean and reliable energy for all) received much attention due to the important positive influence that it has collaterally on the other SDGs (McCollum et al, 2018).[ccl] Considering recent reports (IEA and others, 2019)[ccli], the COVID-19 pandemic has considerably slowed down the electrification effort, resulting for the first time in decades in stagnation that could not keep up with the consistent population growth registered in sub-Saharan countries. Nevertheless, SDG 7.1.1. generated a vivid academic debate concerning the best pathways to achieve electrification in the "Dark Continent" (Tagliapietra and Bazilian, 2019; Trotter et al, 2017).[cclii][ccliii] The vast untapped potential of the continent in renewable energy is clearly highlighted in these studies and reviews, which underline how lack of funding (both private and international) stands as the biggest limit toward this goal. The literature also highlighted the role that hydropower must play in the future electricity generation mix. Falchetta et al (2020) provides three potential generation mixes for East Africa by 2030, with the installed capacity of hydropower growing up to 11GW in all scenarios and accounting for more than 50% of the total energy supply.[ccliv] In their projections, Falchetta also keeps into account the increasing likelihood of extreme hydro-climatic events, which consistently lowers the capacity factor of hydroelectric power plants at 0.55. In the decades to come, hydroelectricity will still play a fundamental role in the generation capacity of the continent. This overreliance on large multipurpose infrastructures, will not come free of risks.

Finally, these social and economic considerations about dam-building, have to be framed in a framework of political decision-making. Consistently high corruption levels in the public sector are present in all the countries considered in this thesis according to the annual Corruption Perceptions Index.[cclv] Decision-makers push these centralized large-scale infrastructural projects framing them as a sort of 'economic development' requirement. Electrification provides clear improvements to social wealth, but the costs of these megaprojects are clear too. Hydropower is frequently justified due to the low cost of generation, but sub-Saharan politicians frequently miss the high financial risks behind their construction. Hydroelectric dams usually require longer to project completion, with cost overruns in over 70% of the construction projects (Winkler et al, 2011).[cclvi] These miscalculations diminish the effectiveness of decision-makers, which end up inadequately weight up the costs and benefits of public developmental projects, but also hurts the investors from the private sector, that suffer the burden of financial loss (Sovacool et al, 2014).[cclvii] Not only internally, but these levels of hydropower dependency also cost each country in terms of political standing and international status abroad, as seen on multiple occasions in the case of mega-projects like the Grand Ethiopian Renaissance Dam in Ethiopia,[cclviii] and the proposed Grand Inga in the DRC (EJA, 2020).[cclix] Leaving aside the socio-economic implications, hydropower projects entail high political costs, which end up failing their promises of cheap and reliable electricity generation to "illuminate Africa". Hydropower in developing countries is considered the majority of times in terms of energy generation. However, a great advantage of large conventional dams specific to areas periodically subject to water scarcity is the role they cover in drought mitigation through their large reservoirs. The operation of large-scale water reservoirs increases the flexibility of transboundary water allocation regimes in response to droughts (Gerber and Mirzabaev, 2017).[cclx] Interregional water management mechanisms are fundamental in order to coordinate the common effort against extreme climatic events. The collective management of transboundary rivers may efficiently reduce the general costs linked to flood and drought events, and provide a more efficient and less vulnerable generation of electricity. This kind of cooperation may also provide an efficient measure of environmental protection, where the aquatic habitat is still impacted, but not in an irreparable manner. Nevertheless, large-scale water projects may become themselves obstacles to transboundary water cooperation, creating a paradox where they necessitate effective transnational mechanisms of cooperation to properly function as drought mitigation infrastructures, while at the same time impairing this same process by creating political tensions and exacerbating downstream riparian countries environmental and social issues (Cooley et al, 2009).[cclxi] In conclusion, the decision-making behind hydropower is strongly biased and tends to frequent miscalculations in terms of financial risks, socio-environmental impacts, transnational political conflict, and not last the efficiency in water management. In the next paragraph, specifically, this last point will be addressed, pointing out the underlying issues concerning hydropower generating efficiency in sub-Saharan Africa, in a context of seasonal water scarcity and of the growing material effects of extreme climatic events in the region due to climate change.

2.4 Drought events and hydropower generation linkages in Africa

Hydroelectricity generation entails kinetic or potential energy exploitation. Whether small run-of-the-river or conventional large dams, all forms of hydropower plants depend on water availability as the necessary input source for achieving electricity generation. The discussion presented in the last two chapters tried to represent the importance of considering the energy system as something logically interlinked to both water and climate. The considerations made until now mainly focused around the hydrological context of dams, where consumption of the water input necessary to generate electricity is often in competition, with agricultural use, municipal use, and maybe negatively influenced by inter-annual variation in rainfall. This paragraph, however, looks in a more specific way towards the ‘electricity generation aspects’ of dams. In consideration of the relevant water-scarcity literature which has already been presented in the second chapter of this thesis, it is logical to assume that in light of the increase in extreme climatic events, dependency on hydropower may create serious challenges also for future energy security. The recent climate change-related literature sparked an intense debate concerning the impacts of global warming on electricity generation. In order to successfully understand these systems, scholars must consider a variety of temporal scales with a geographic perspective that usually stretches for entire countries or regions, especially when factoring in transboundary water basins. A comprehensive approach to a spatiotemporal water-power model is found in Pereira-Cardenal et al. (2014),[cclxii] where an assessment of the Iberian Peninsula underlines the vulnerabilities of its water-dependent power system. In their work, they provide an important assessment and framework concerning the water-energy relation, which criticizes the traditional method of modeling energy and water systems in isolation, as separate entities not linked to one another. The actual reality is quite different, and due to the nature of their interrelationship, it is impossible to successfully analyze a system, without keeping into account the interdependency with the other (Pereira-Cardenal, 2016).[cclxiii] Subsequently, at Wageningen University, Michelle van Vliet and her colleagues (2016) attempted to quantify the potential impacts of drought events on water-dependent power plants by using a coupled hydrological–electricity modeling approach. This study included both hydroelectric and thermoelectric generating systems, providing a greater understanding of the quantification of potential impacts of increasing temperatures on the global electricity supply.[cclxiv] Using data from a variety of future climate scenarios, they provide further evidence of how entire macro-regions will witness a severe reduction in streamflow, which critically reduces efficiency in hydropower and thermoelectric power plants. Such perspective on the water-energy nexus is followed in this master thesis. However, the two studies use a rainfall and runoff model where they aggregate meteorological datasets (precipitation, temperature, altitude) and combine them to electricity outputs in order to evaluate the efficiency of power plants requiring water for cooling (nuclear, thermoelectrical) or generation (hydropower) purposes. Thus, datasets required for these calculations need to be updated and reliable. Nevertheless, both these studies and other region-specific case studies provide extremely compelling evidence of the current and future situation of energy studies. While the authors discussed in this paragraph limit their research to a geostatistical analysis of the relationship between extreme events and electricity generation, with the first part of the thesis it is possible to support these considerations with different perspectives on the social and economic ramifications of climatic impact

Considering the geographic area selected for this study, however, by comparing the ICOLD, GPPD, and GRanD databases, limits of these theories were visible as specific information on the specifics of the reservoirs were either lacking data or of limited quality. Other scholars already pointed out the grave lack of qualitative and quantitative data in developing countries, with the situation being particularly grave in the low-income countries of sub-Saharan Africa (Larsen et al, 2019).[cclxv][cclxvi] It is important to remind that wide differences in evaporation rates and drainage characteristics exist in different areas of a basin, which influences the overall discharge of the watershed. Furthermore, irrigation use may be underestimated due to illegal withdrawals that may influence water levels in reservoirs. These factors are hard to keep track of, especially in areas plagued with low data collection and accessibility like the low-income countries discussed. Instead of relying on field gauge observations, which are relatively more precise but scarcer in presence, a satellite remotely-sensed approach was pursued. This called for the factoring of climate in the hydrological factors calculated. So as to find the critical years during which hydropower generation may have been impacted, consistent grid-cell satellite data regarding precipitation and potential evapotranspiration was collected and cropped for the region of interest. The specific areas regarding the dam location (as provided in **Table 2**) are then collected and confronted with the climatic data. In these locations, the SPI (Standardized Precipitation Index) and the SPEI index (Standardized Precipitation Evapotranspiration Index) are calculated and used on different monthly timescales.[cclxvii] In Falchetta et al (2020) empirical evidence has been provided on the functionality of open climate remotely sensed datasets and how they can provide a reliable benchmark to evaluate the impacts of extreme climatic events on hydropower reliability in regions of the world where data is scarce or limited.

Water is obviously the fundamental input, which requires different conditions in order to provide reliable generation of power, based on the type of dam selected. The availability of water resources is conditioned by several meteorological and non-meteorological factors, which tend to influence the main water sources in different ways. Generally speaking, run-of-the-river are more vulnerable, thus prone to reduced efficiency, to changes in precipitation and runoff, since the electricity generation process in these plants depends on the rivers flow. The high seasonality of rainfall in Africa increases the overall uncertainty regarding the stability of water inputs and power reliability. While conventional large dams tend to be less subject to reduced runoff levels, they have shown the tendency to experience vulnerability to temperature and evaporation events (Blackshear et al 2011).[cclxviii]

Extreme events of rainfall (both scarcity and excess) and temperature patterns produce drought or flood cases. The effects of drought events are not immediate and become visible after a relatively long period of precipitation shortage, thus creating difficulties in trying to objectively evaluate the onset, duration, intensity, and geographic extent of these episodes. Conceptual subjectivity in the definition of drought events generates certain ambiguities in the scientific literature, which creates obstacles towards the establishment of a single universal drought index. The first climate index, used in countless scientific studies, and considered in this thesis is the Standard Precipitation Index (SPI) (McKee et al, 1993).[cclxix] The SPI is a commonly accepted and multi-scalar index, which calculates the standard deviations of the cumulative precipitation over a personally selected timescale. With a specific focus on rainfall variability, the SPI is a valuable indicator of medium and long-term wet and dry periods in the hydrological cycle. As a precipitation-based index, SPI gives a higher focus to precipitation than to other variables. In order to test the influence of other climatic variables that may influence drought conditions like evaporation and temperature increase, due attention was consequently paid to the SPEI index (Vicente-Serrano et al, 2010).[cclxx] Accounting for evapotranspiration on water bodies, it detects and analyzes droughts periods and severity by examining the water balance modeled by the difference between the precipitation (P) and potential evapotranspiration (PET) for the selected time period *i*.

$$\mathbf{D_i = P_i - PET_i}$$

With each different index providing its own pros and cons during an assessment, a vast scientific literature concerning drought estimation has been produced concerning using both the SPI and SPEI indexes as a reference in the analysis of extreme events impacts and duration (Stagge et al, 2017; Oikonomou et al, 2020).[cclxxi][cclxxii] Different timescales can be used by both indexes in order to analyze the presence and persistence of drought periods. A 6-month SPI calculation would be better suited to reveal the seasonality behind precipitation patterns in a medium-trend in water resources, and considering a 6 to 12-month scale may evidence irregularities in reservoir storage, thus indicating an event of hydrological drought (Karavitis et al, 2012).[cclxxiii] According to Lorenzo-Lacruz and his colleagues (2010),[cclxxiv] even though reservoirs have the ability to mitigate water scarcity caused by reduced precipitation, they are still subject to evapotranspiration effects. In their work, a positive correlation is found using both SPI and SPEI indexes, with the latter being especially suited to accounting for water outputs due to meteorological conditions, especially in medium and long-term timescales. In order to examine the impact of extreme events, 3-, 6- and 12- month SPI and SPEI calculations are used. As clearly explained in Kumar et al (2009), for the purpose of computing the SPI, long-term data on precipitation is required, with the goal of determining the probability distribution function which is then transformed to a normal distribution with a mean zero and standard deviation of one.[cclxxv] In accordance with the process followed by Vicente-Serrano and his colleagues (2010), the basis of the calculation is true for both SPI and SPEI indexes.[cclxxvi] In conclusion, the values expressed in both indexes are standard deviations, with a positive SPI value designating greater than median precipitation, and negative values indicating less than median precipitations. Concerning the intensity of events observed in SPI and SPEI, a variety of scholars produced different representative values for different purposes, but in this text, the representation of dry and wet spells will be based on McKree et al (1993) as seen in **Table 1.**

SPI and SPEI value	Climatic Event Intensity
≥ 2	Extremely wet
1.5–1.99	Very wet
1.0–1.49	Moderately wet
−0.99 to 0.99	Near normal
−1 to −1.49	Moderately dry
−1.5 to −1.99	Very dry
≤ − 2	Extremely dry

Table 1: Extreme event classification based on SPI and SPEI index (McKree et al 1993).[cclxxvii]

After collecting all the data relevant to this work, the main hydroelectric power units in the panel countries were selected and reported in **Table 2** (Chapter 3). No clear distinction is made regarding the local climate of each dam, but power plants are selected by following certain criteria as follows

- **Operational status of the dam**: power unit had to be in function during the whole period of time and fully operational.
- **Temporal scale**: the time period selected between 1992 and 2013 (due to data availability) required that power units considered had to be operational since 1992, or at least for half this time scale.
- **Generation capacity**: considering the nature of this thesis, every power plant under 40 MW of generation capacity was excluded, since smaller dams that may have been built on the same basin may mitigate the reduced efficiency thanks to bigger reservoirs upstream.

Since the effect of intra-seasonal variation in average temperature through evapotranspiration and melting is already captured by the SPEI index, it was not separately considered. A buffer zone of consideration of around 10 kilometers, in order to account for the different dimensions, of water basin and reservoirs included in the assessment. Conclusively, it must be underlined how overall consumption of water inputs in power generation rests on different site-specific and technological variables (i.e. water turbines, dimension of the head, dimension of reservoir, electricity generation, or multipurpose). The total demand for water inputs in hydropower is subject to the type of power unit and the technology employed, which therefore breaks down between conventional large dams and RoR plants. RoR lacking water reserves (or provided with very small water capacity) are particularly vulnerable to extreme events as stated before. Nevertheless, short-lived droughts, as well as seasonality and long-term changes in water supply induced by climate change or other anthropogenic drivers can have a considerable impact on effective generation capacity (Falchetta et al, 2019).[cclxxviii] An assessment concerning the water footprint of energy-generating technology calculates 96.4% of water consumption in Africa due to hydropower plants (Mekonnen et al, 2015).[cclxxix] Thus, the over-reliance on hydropower generation for sub-Saharan countries amplifies consumption of its water resources, which to some extent may heighten the effects of extreme events assessed in this work. In conclusion, the geographic context pertaining to this study is one where water infrastructure capacity is either minor or absent. Aggravated by the presence of extreme events, the situation necessarily asks for further considerations on the nature of the endemic condition of scarcity in the water and energy context, especially in regard to the current socio-economic structure. The fundamental role that agriculture plays in sub-Saharan society, requires further attention on the current water infrastructure, in light of the progressive change in rainfall intensity.

3. Methods and Datasets

"It is not down on any map; true places never are."

Herman Melville

3.1 Reservoirs datasets

In the following section are presented the datasets and general methods used to undertake the quantitative analysis. First, it was necessary to find the specific location of the different hydropower plants in the selected panel countries. In order to obtain specific and precise geographic data, information concerning the hydropower plants' characteristics was collected by comparing three different datasets. The Global Power Plant Database is an open-source open-access dataset of grid-scale (1 MW and greater) electricity generating facilities operating across the world.[cclxxx] Detailed information is provided regarding the expected capacity of each dam. This was cross-checked by personal research on search engines, correcting or completing the information present. Furthermore, data were collected from the Global Reservoir and Dam Database (GRanD) which provided other information about cities located near the chosen reservoirs.[cclxxxi] Finally, the International Commission On Large Dams (ICOLD) World Register of Dams (WRD)[cclxxxii] which provided additional information on the power plants. All the information from these databases complemented each other and was merged to generate a selection of 37 hydropower units. The selection followed a series of spatial and temporal criteria. First, units had to be selected based on geographic relevance based on the panel of countries presented at the end of the first chapter. Some dams are built quite close to the national boundaries with other countries, usually providing electricity for both nations. Secondly, dams built after 2010 were excluded due to the temporal limitations of the climatic and illumination datasets. Precedence of information was given to plants found in the Global Power Plants Database since it reports on-grid power supply units. A specific decision to exclude every power plant under 40 MW of generation was made. This specific decision was taken with the purpose of avoiding the computation of small reservoirs that would get compensated by bigger power plants or simply show little impact on the overall radiance level of the region.

Finally, the pool of countries selected for the quantitative analysis of the climatic and nighttime illumination data represents an important basin of reference for the interaction between climate and water-energy systems described in the previous chapter. The selection of the countries has been evident in all the graphs made at this point and is represented by: ***Angola, Democratic Republic of Congo, Republic of Congo, Mozambique, Kenya, Namibia, United Republic of Tanzania, Sudan, Zambia, and Zimbabwe***. These countries cover a variety of diverse climates, habitats, and geographic conditions, thus providing an interesting pool of research. The wide local differences present in the electricity sector and generation mix of this country also provide an interesting factor of analysis. In ***Table 2***, all the selected dams are represented with their relative geographic location, country name, year of commissioning, and the installed generation capacity in megawatts from their turbines.

Country	Dam	Capacity MW	Lat	Long	Year of Commissioning
Ethiopia	Awash II	64	8.39	39.35	1996
Ethiopia	Beles	460	11.81	36.91	2010
Mozambique	Cahora Bassa	2075	-15.58	32.70	1974
Angola	Cambambe	180	-9.75	14.48	1963
Angola	Capanda	520	-9.79	15.46	2004
Mozambique	Chicamba	44	-19.15	33.14	1959
Mozambique	Corumana	166	-25.21	32.13	1988
Ethiopia	Fincha	134	9.55	37.36	1973
Ethiopia	Gilgel Gibe I	184	7.83	37.32	2004
Ethiopia	Gilgel Gibe II	420	7.75	37.56	2010
Kenya	Gitaru	225	-0.79	37.74	1978
Democratic Republic of the Congo	Inga II	1775	-5.52	13.62	1982
Zambia	Itezhi- Tezhi	120	-15.76	26.02	1978
Zambia	Kafue Gorge	990	-15.8089	28.41	1971
Kenya	Kamburu	94.2	-0.80	37.68	1974
Kenya	Kiambere	168	-0.64	37.91	1987
Tanzania	Kidatu	204	-7.63	36.88	1975
Tanzania	Kihansi	180	-8.57	35.85	1999

Kenya	Kindaruma	72	-0.80	37.81	1968
Ethiopia	Koka	43.2	8.46	39.15	1960
Democratic Republic of the Congo	Koni	42	-10.71	27.28	1950
Kenya	Masinga	40	-0.87	37.58	1980
Angola	Matala	40	-14.73	15.03	1954
Ethiopia	Melka Wekana	153	7.17	39.43	1983
Republic of Congo	Moukoukoulou	74	-3.89	13.76	1979
Tanzania	Mtera	80	-7.13	35.98	1980
Democratic Republic of the Congo	Mwadingusha	68	-10.74	27.24	1930
Democratic Republic of the Congo	Nseke	260	-10.30	25.40	1956
Democratic Republic of the Congo	Nzilo	228	-10.50	25.44	1957
Tanzania	Pangani Falls	68	-5.34	38.65	1995
Democratic Republic of the Congo	Ruzizi I	81	-2.63	28.90	1958
Kenya	Sondu Miru	60	-0.34	34.85	2007
Ethiopia	Tekeze	300	13.34	38.74	2009
Ethiopia	Tis Abay I	84.4	11.48	37.59	1964
Kenya	Turkwel	106	1.91	35.34	1990
Democratic Republic of the Congo	Zongo 1	75	-4.77	14.90	1945
Sudan	Merowe	1250	18.66	32.05	2009
Sudan	Roseires	233.6	11.79	34.38	1961
Zimbabwe	Kariba Dam	750	-16.52	28.76	1960
Namibia	Ruacana	240	-17.38	14.21	1978

Table 2: *Hydroelectric power plants by country, name, capacity, coordinates, and year of commissioning.*

The geographic coordinates from these power plants were collected and spatially represented on polygon layers of the respective national territories. The national boundaries represent a merely graphic purpose, to show different specificities among which are the proximity to borders of certain dams and how disruption of electricity supply due to climatic events may have transboundary and transnational impacts. National boundaries were represented in the shapefile created by Bjorn Sandvik (2009).[1][cclxxxiii] Another shapefile (shapefiles are the common data format for geographic information systems) was used as a graphic instrument to offer a clearer view of the topic discussed.[cclxxxiv] The HydroRIVERS dataset provides a global coverage of river reaches high spatial resolution, each with a reference to the corresponding transboundary basin system of origin. Different levels of sub-basin breakdown are offered, but a specific choice was made to use only the first and the most general layer of reference. Figure 4 provides a graphic representation of the national boundaries of the sub-Saharan countries, the main river networks of each nation, and the location of the selected hydroelectric power plants.

[1] *Shapefiles are a popular geospatial vector data format for geographic information system (GIS) software*

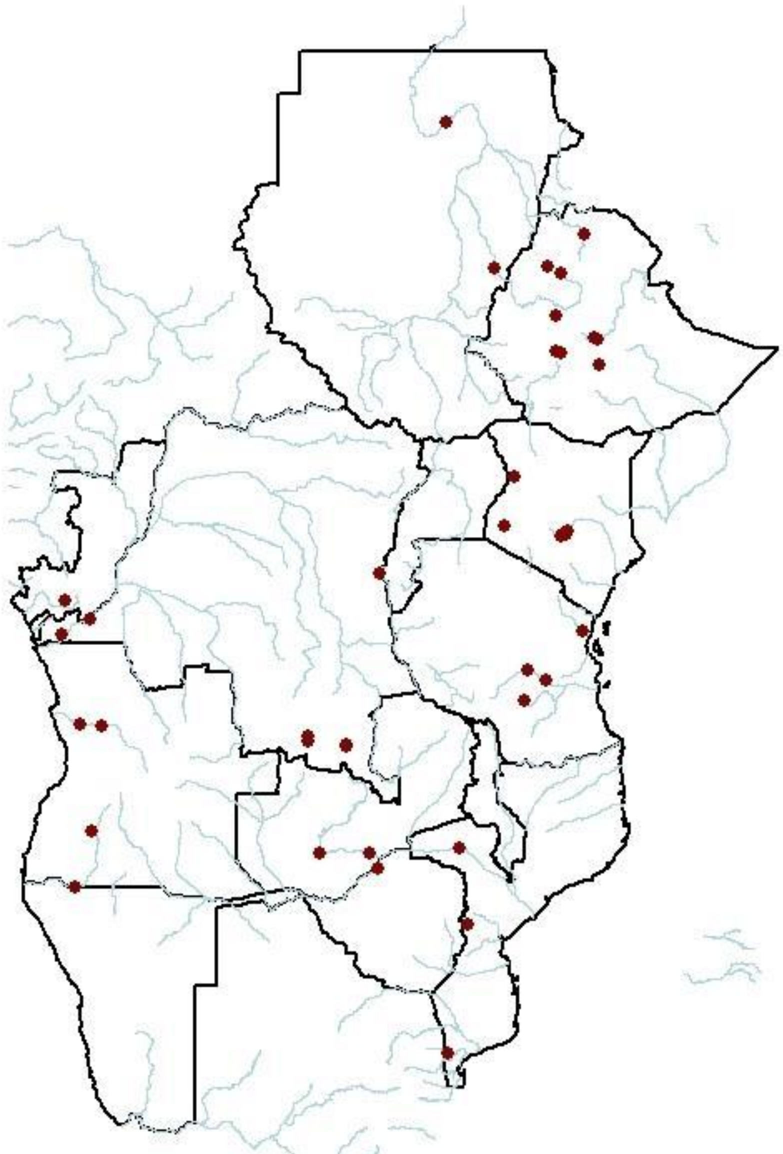


Figure 4: *Political map of sub-Saharan Africa national boundaries and main river basins. Dark green points represent the geographic location of selected power plant units. Source: Own elaboration based on the 'World Borders Dataset', the 'HydroRIVERS' dataset and the collection of 'ICOLD', 'WRD', and 'GRanD' described in the last paragraph.*[cclxxxv][cclxxxvi]

3.2 Drought Index datasets

In order to identify the relationship between drought events and electricity generation, which is one of the objectives of the thesis, both the Standard Precipitation Index (SPI) and the Standard Precipitation Evapotranspiration Index (SPEI) have been calculated. Both these indexes have been created to specifically analyze the variety of drought events, whether of hydrological, agricultural, or meteorological nature. Further specific information and insight concerning SPEI and SPI indexes and why they matter will be provided in the next chapter.

Climate sciences made a priority over the development of global gridded datasets at different timescales that could report the various important climatic variables such as temperature, pressure, and precipitation. Nevertheless, these datasets alone are not sufficient to explain a complicated natural phenomenon, like that of extreme climatic events (namely droughts and floods) (Heim, 2002).[cclxxxvii] Drought indices have evolved to guarantee precise problem-specific solutions and to realistically represent the magnitude, intensity, and duration of these natural events. Considering the aim of this thesis, to search for a possible relationship between drought events and reduce electricity generation, both the Standard Precipitation Index (SPI) and the Standard Precipitation Evapotranspiration Index (SPEI) were employed.

The process and methodology to calculate the SPEI index are found in the Global SPEI database provided by the SPEI Global Drought Monitor (Vicente-Serrano et al, 2010).[cclxxxviii] The SPEI index calculation is elaborated on the same basis as the SPI, with the addition of evapotranspiration as a determining variable in drought events. The necessary primary data concerning precipitation and evapotranspiration values used in this research are the Climatic Research Unit (CRU) TS4.03 dataset.[cclxxxix] This new dataset has received wide recognition in the scientific community due to the high precision of the spatial resolution at a global scale. Other advantages provided by the CRU dataset are that it has spatial and temporal compatibility to the timescales necessary to calculate the SPEI and SPI index, and presents all the variables necessary to successfully detect the variety of existing drought event types. These high-resolution global-gridded historical datasets (namely precipitation and evapotranspiration datasets) are available in netCDF (Network Common Data Form) format, which is the standard default for gridded time-series data in the earth system modeling community. These englobe monthly observations which provide values for each year from 1901 until 2018 at a fine spatial resolution of 0.5° x 0.5° degrees. In order to manipulate and analyze the datasets, the use of R Studio (Core Team R, 2019) is required.[ccxc] R is a language commonly used for statistical computing, which was fundamental in the computation of the datasets analyzed. These datasets have been accessed with the R-software package “ncdf4 (Pierce, 2017).[ccxci] Later, the precipitation and potential evapotranspiration datasets from the CRU are used to calculate the drought indexes with the package “SPEI” (Beguerìa and Vicente-Serrano, 2017).[ccxcii] After a final step of data manipulation, the SPI and SPEI values are finally calculated using the Gamma distribution. These values are used with the R-package ‘exactextract’ and ‘rgdal’ to extract values for the specific area of the selected power hydropower plants (Baston, 2021; Bivand et al, 2021).[ccxciii][ccxciv] Values are represented on different timescales, among which, 3, 6, and 12 months were selected as the main reference for short, medium, and long-lasting drought events. As reservoirs may hold significant amounts of water offsetting the effects of small-scale droughts, this timescale was a necessary step to avoid statistical errors. Both indexes are used to measure the intensity of drought events, with each providing its own specific advantages. The SPI index is expected to offer more precision for run-off-the river plants and small reservoirs, which are highly dependent on water levels and precipitations, while the SPEI index includes in its calculation evaporation and temperature effects (making it particularly useful also for climatic impacts on agriculture), elements that may influence more conventional large dams with large reservoir capacity. Furthermore, accounting for the average temperature, the SPEI index is expected to be able to find a negative correlation in mountainous areas. This expectation is made due to the impact that higher temperatures would have on snowpack melting, which would thus increase the water levels. This is an interesting piece of information that would provide an accounting of not only drought events, but also flood events’ impact on the energy supply.

The R-packages cited above represent the most important libraries, among the many used in order to achieve the results presented in the following chapter. With the aim of demonstrating the validity and reproducibility of these outcomes, a repository for data availability will be offered, to offer the readers the possibility of verifying the results, and if possible, apply some aspects of the datasets provided to further investigate climatic or socio-economic aspects of the geographic area taken into consideration in this research.

3.3 Night-time illumination intensity datasets

After the selection of drought-indexed datasets, nighttime light data was used as a proxy variable for electricity access and generation reliability. The source of reference is the National Oceanic and Atmospheric Administration's Defense Meteorological Satellite Program (DMSP)/Operational Linescan System (OLS) stable nighttime light (NTL) dataset. This system collects daily images between 8:30 pm and 10:00 pm local time, and after cleaning and processing these images, NOAA averages them across each year and distributes annual composite images online. Each yearly dataset reports light intensity for every 30 arc-second pixels (approximately 1 km2 at the equator) on a 0–63 scale, which is proportional to the average observed luminosity.

The employment of DMSP/OLS-NTL data is supported by a solid corpus of academic research and has been widely employed in a broad range of research sectors, which span from socioeconomic, to electricity generation activity and population distribution (Chen and Nordhaus, 2011; Doll and Pachauri, 2010).[ccxcv] [ccxcvi] The Global DMSP/OLS stable NTL employed in this research has been processed by Li and Zhou (2017).[ccxcvii] They calculate and provide access-free a calibrated version of nighttime light data, made from a composite of annual cloud-free observations from six different satellites, with global coverage and a long-temporal record of 22 years, spanning from 1992 until 2013. The changes in nighttime illumination brightness observed from space are used in this research to suggest a variation in electricity supply in the urban areas of the selected countries. Chand et al (2009) and Min (2011) found in their respective works how nighttime lights had a direct relationship with power consumption in India. In addition, recent studies successfully demonstrated how satellite-derived radiance has the potential to assess the magnitude, spatial extent, and duration of net power losses (Roman et al 2019).[ccxcviii] Finally, recent research was successful in evaluating the impacts of extreme climatic events on disruptions of electricity supply (Wang et al, 2018).[ccxcix] In conclusion, this literary corpus seems to suggest how NTL radiance brightness is an efficient surrogate of energy consumption in rural areas or where data is limited. All in all, some evidence of supply disruptions has been found in previous works, thus suggesting how blackouts or brownouts are both visible from space and can be correlated to long-term events like droughts in contexts where energy is highly-dependent on water inputs. In the following paragraph is provided a brief review that further consolidates evidence on the usefulness and efficiency of NTL brightness as a proxy for electricity supply in data-scarcity condition, and how it has been employed in this research.

Different scholars like Doll and Pachauri (2010) provided evidence on how certain black spots, where night illumination satellites cannot detect visible light, are either uninhabited or areas where the population does not have access to electricity.[ccc] The majority of the African population inhabits rural areas. These are commonly harder to reach and to connect to the national grid, thus lacking access to electricity more frequently than their urban counterparts. In order to locate the most important urban centers in the panel countries' territory, the World Cities Database was used.[ccci] This up-to-date database covers up to 41 thousand cities and towns, also offering some additional information such as population count and geographic coordinates. While the population count for the selected urban centers is seemingly a conservative estimation, according to the World Cities Database the urban areas selected from this database and assessed in this thesis are inhabited by more than 110 million people. Using the DMSP-OLS NTL dataset at a fine spatial resolution of 1-km, it is possible to subsequently aggregate yearly data of night-time illumination for the coordinates found in the World Cities Database, with a buffer area of 10km around the urban centers. A multitude of studies provided supporting evidence of the potential of satellite-based nighttime imagery as a modern tool of geostatistical analysis in developing countries where data is severely limited (Andrade-Pacheco et al., 2019).[cccii] In particular, Falchetta and others (2020) recently provided empirical evidence of the functionality of high-resolution data in estimating the effective increase in overall electrification access in sub-Saharan Africa in the period between 2014 and 2019.[ccciii] The number of people provided with electricity access grew at a constant rate, reaching an estimated 47% in the period of reference in his work, with this increase being achieved despite the growing population in the region (by 14%, i.e., +144 million). A robust corpus of research thus confirms the application of nighttime illumination data has a successful proxy for electrification access, electricity consumption, and even economic growth (Burlig and Preonas, 2016).[ccciv] Several considerations, however, have been noted by the authors listed and must be discussed in order to use NTL as an electricity supply proxy. For example, the fact that these measurements happen limitedly overnight at the passage of the satellite. Furthermore, the observation made by the satellite includes every form of visible light radiance, thus including public lighting. The last important limitation of the DMSP/OLS dataset comes from the fact that nighttime illumination observed must have a sufficient intensity in order to be detected by the sensor (Falchetta et al, 2020). This very low level of final use required is the threshold of both the DMSP/OLS observation and this work, since all the selected power units are grid-connected, thus more likely to supply urban centers rather than rural areas. Other important limiting factors present in this thesis that are not kept into account in the final results are the presence of gas-fired backup generators (IFC, 2019),[cccv] which account for 135 GWs of installed capacity in sub-Saharan Africa. In conclusion, the final unaccounted factor is that the observation of electricity consumption happens overnight, when statistically speaking overall consumption of electricity is much lower compared to the rest of the day. These are the main uncertainty factors that may downsize the intensity of the results obtained in consideration of the instruments used. The results will be provided and discussed in the next chapter. Figure 5 reports a visual representation of the 512 urban centers found in the database for the selected countries and their location compared to the main dams.

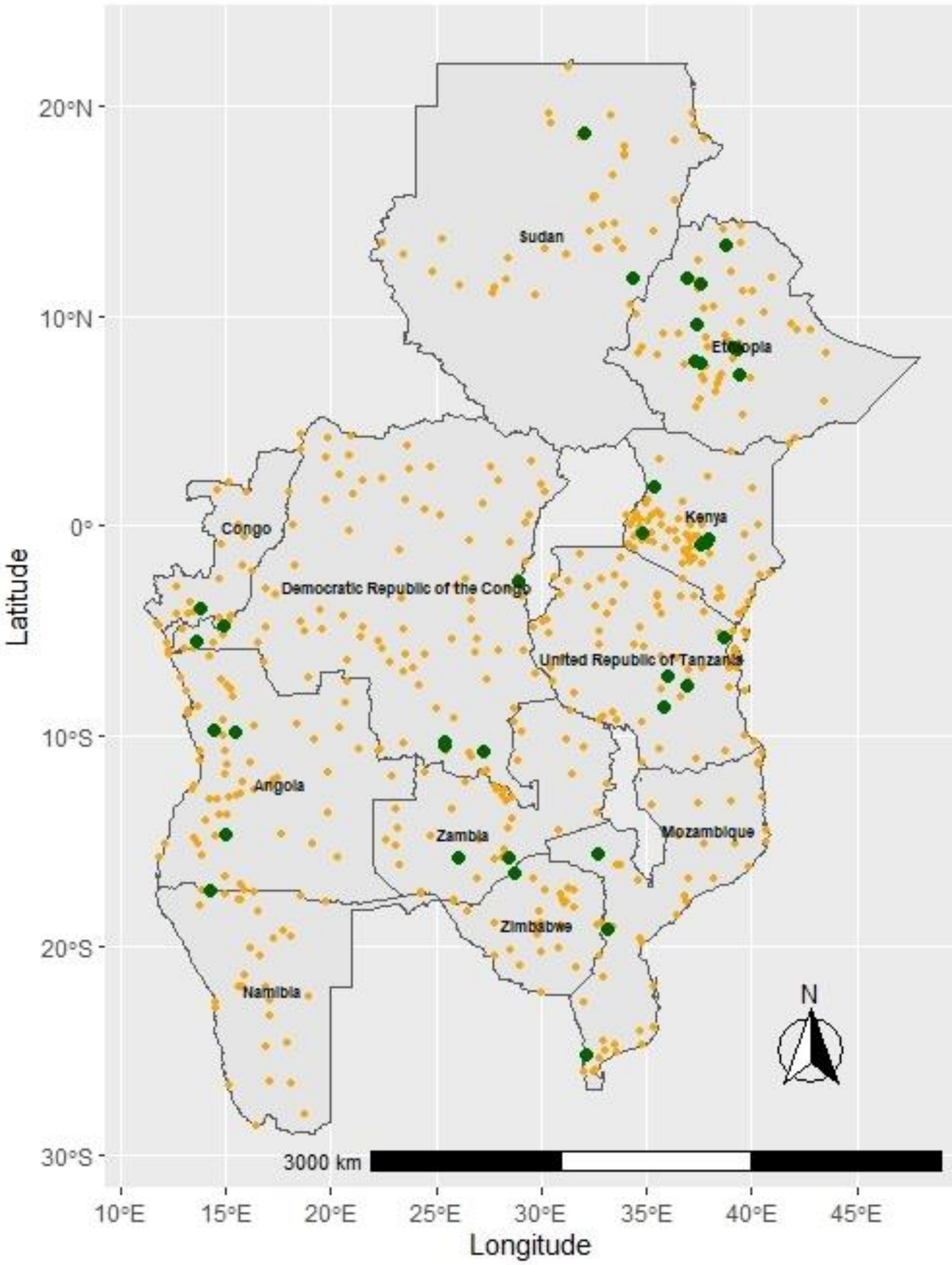


Figure 5: *Map representing the political boundaries of each sub-Saharan nation discussed, as found in Sandvik (2009),[cccvi] with the locations of the selected hydropower plants (dark green) and the main urban centers (orange) as found in the World Cities Database.[cccvii] Source: Own elaboration and mapping based on the data sources described in this chapter (World Cities Database, ICOLD, GRanD, World Borders Dataset).*

4. Quantitative evidence of extreme events on sub-Saharan energy supply

"*They don't want to see developed Africa; they want us to remain undeveloped and backward to serve their tourists as a museum*".

Prime Minister of Ethiopia Meles Zenawi.[cccviii]

"[…] then I asked the NGOs, why can't you commission or finance these studies? You only know how to ask questions!"

Minister of Water Resources and Electricity in DRC Congo.[cccix]

In light of the previous chapters, the academic literature discussed provided empirical evidence of how the water and energy systems, which both influence hydroelectricity generation, must keep into account the climate system where they develop. This is particularly true in certain regions like sub-Saharan Africa, where the high inter-seasonal variation of rainfall, frequent competitive use of water resources, and high dependency from hydropower generation. With these considerations established, I progress to the final part of this thesis.

The quantitative analysis provided in this chapter has the aim of providing data-based evidence of the discussed impacts generated by the climate system over the water and energy system in the specific countries selected. Using these remote-sensed datasets has the objective of pushing forward the discussion on this region-specific Climate-Water-Energy nexus, confirming to a certain extent the existence of a direct influence between these systems. By identifying a statistical correlation between drought events, the aim is to:

1) Provide a 'hydropower perspective' on the CWE nexus and confirm the existence of sensible impacts of drought events on the water-energy systems in sub-Saharan Africa with a data-based approach.
2) Advance the use of NTL data in a context of scarcity of data and as an efficient estimator of electricity supply in a context of medium and long-term extreme climatic events.

The principle behind the use of the DMSP/OLS dataset and the climatic indexes SPEI and SPI and the quest for a causal relationship behind them has been already described extensively in the previous parts of this work. The previous chapter mentioned the use of the R language (Core Team R, 2019) as a fundamental instrument for the statistical analysis presented in this thesis.[cccx] In the script used, the data processing part was made up of 40 hydropower plants, 512 urban centers, and spanning 22 years from 1992 to 2013. After different data processing steps, the resulting data frame consists of 11,264 entries representing buffer zones around each dam (with values from the SPI and SPEI indexes), and the buffer area of 10 kilometers around the urban centers (for the observation of the DMSP/OLS nighttime illumination radiance levels). The extraction of values is carried out with a specific function that selects each monthly value for the SPEI and SPI values and reorganizes these data in a yearly average for the years between 1992 and 2013. Nighttime illumination radiance levels are already organized in average values of each year considered in the model.[cccxi]

The average levels are calculated in correspondence with the power units (for the SPEI and SPI indexes) and the urban centers (for the NTL brightness). Finally, each urban center is merged to the closest power unit in the proximity-based on a GIS algorithm. Thus, the final dataset holds the location of each city and the power unit of reference, which may be logically repeated in cases where different cities are close to different power units. After a final step of data processing, illumination radiance level outputs and the SPEI and SPI values are finally tested. With the objective of this calculation being that of assessing whether a statistical relation between extreme events and NTL exists, the response variable used is the nighttime illumination radiance level, while the predictor variable is represented by the SPEI or SPI indexes. As previously explained, both drought indexes are modeled separately at the different timescales of 3-, 6-, and 12- month values, in correlation with the nighttime illumination levels, to better represent the temporal variability between the results and the different types of drought events.

Using a statistical function on R, the results are reproduced over a scatter plot representing the overall situation of the region discussed in the thesis between 1992-2013. In Figure 6, the regression line is calculated using a sum of squared residuals linear minimization approach. The correlation value represented by **R** is calculated with the '**Pearson'** method. Finally, the horizontal axis represents the drought index of reference (in this case SPEI 6-)

around the buffer zone of 10 km previously described, and on the vertical axis, the NTL radiance levels collected around urban centers in correspondence to the specific average climate of dams. the NTL values are represented on the y-axis and the SPEI and SPI 6- values are represented on the x-axis. The correlation becomes evident, as seen in Figure 6, with a correlation coefficient of R= 0.14 for the SPEI6 and R=0.094 for the SPI6. Similar results are seen in Figure 7 and Figure 8, with the same correlation made for the SPI/SPEI values calculated over 3- and 12- months with the same temporal and geographic extension.

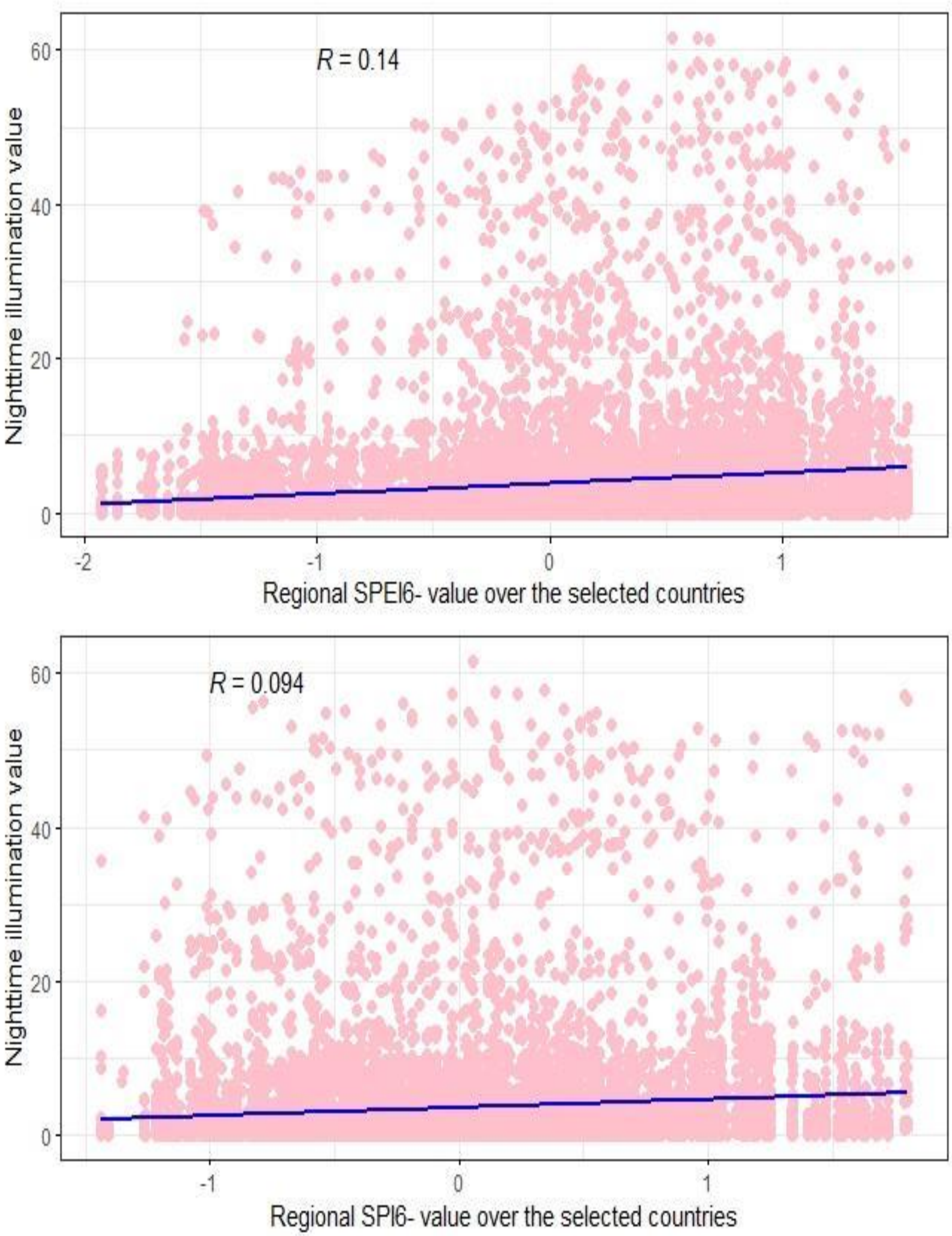


Figure 6: Scatterplot representing the correlation coefficient and the regression line between NTL and SPI/SPEI 6- values on the complete time-scale over the region of interest.

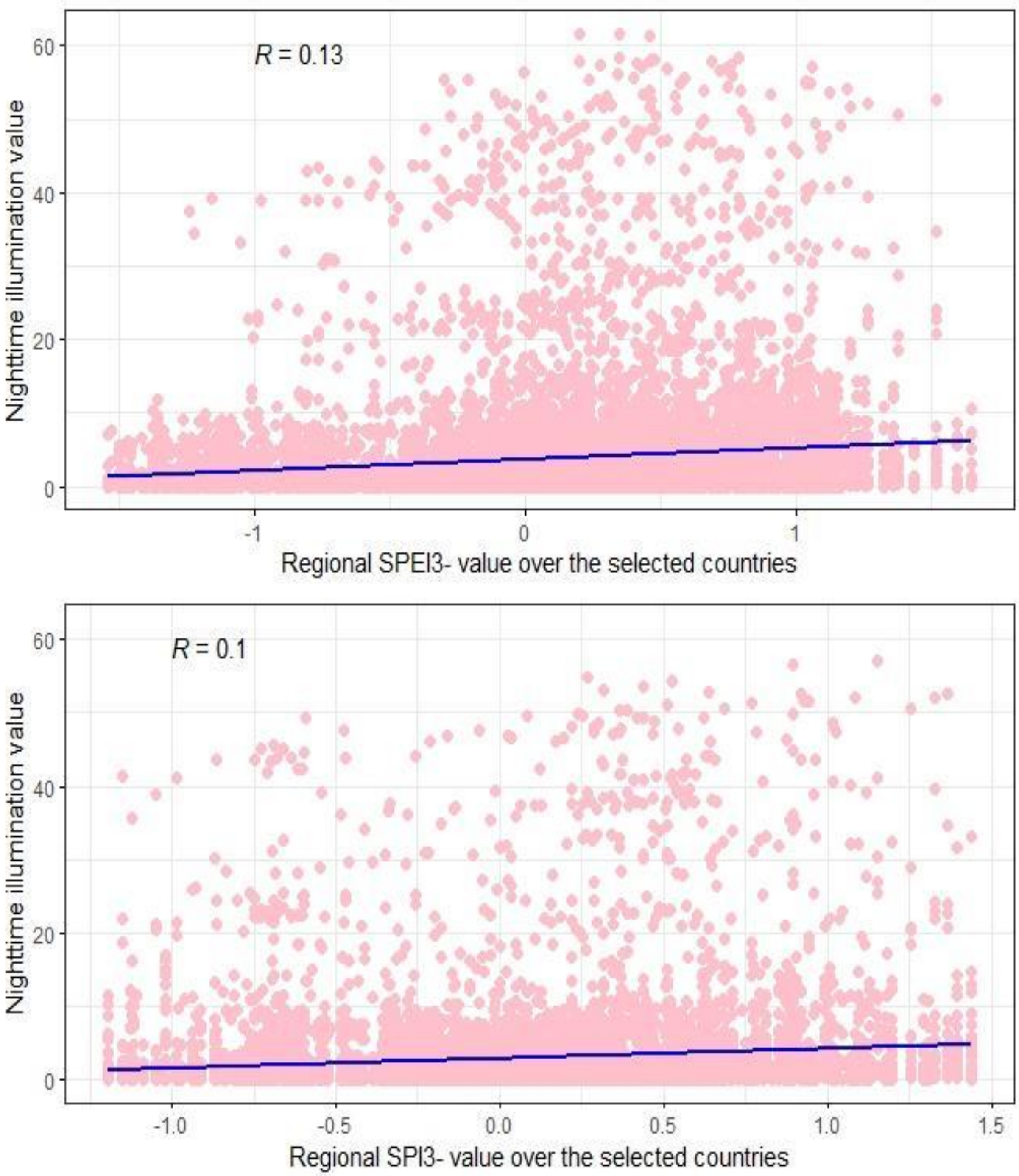


Figure 7: Scatterplot representing the correlation coefficient and the regression line between NTL and SPI/SPEI 3- values

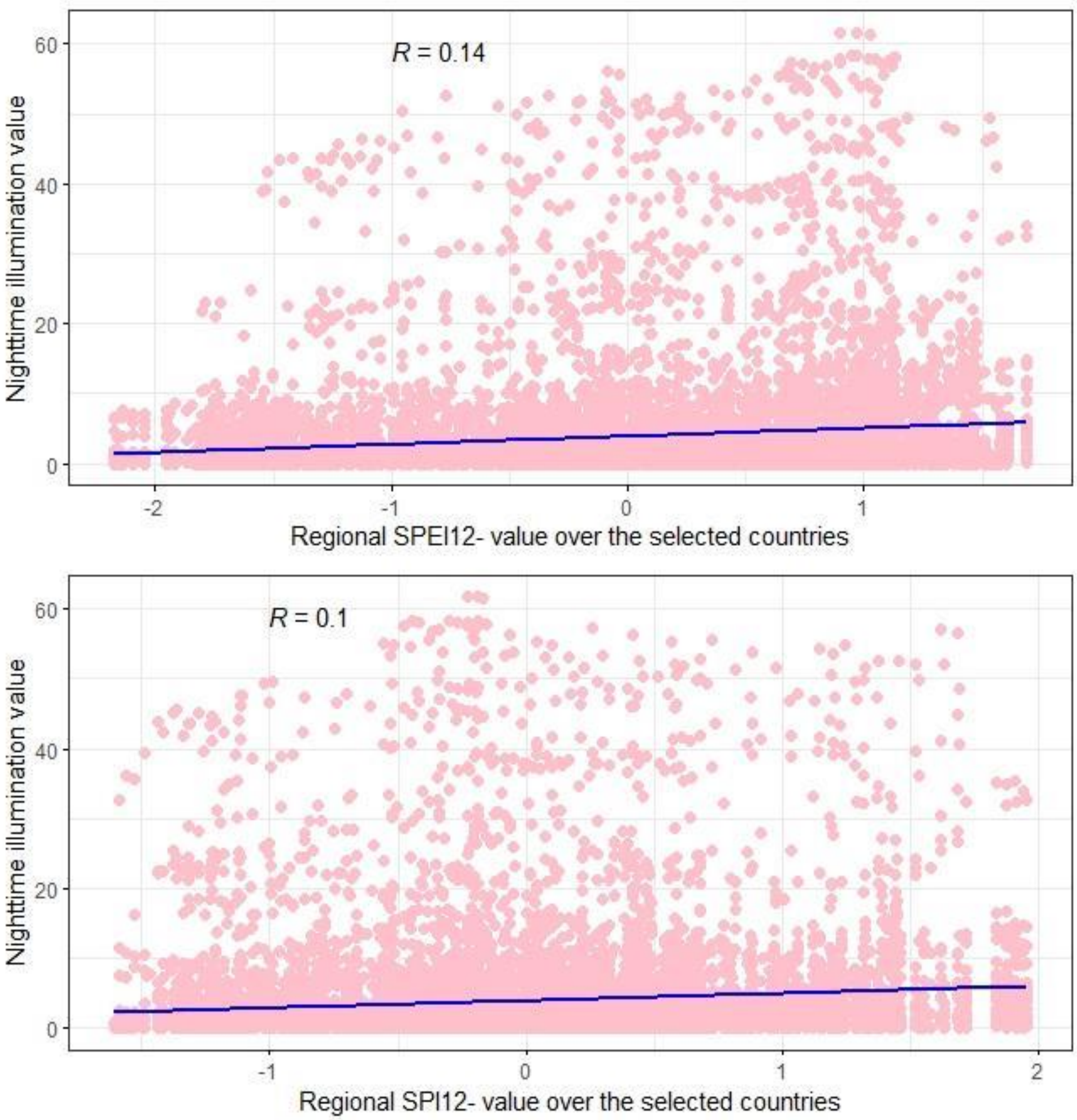


Figure 8: Scatterplot representing the correlation coefficient and the regression line between NTL and SPI/SPEI 12- values.

This kind of data visualization enables a simpler perception of the facts at hand. With the presence of the regression line, the graphs show an overall positive influence of climate events on energy supply with a low, but nevertheless statistically significant, correlation coefficient. As already expressed before, high values of SPEI and SPI imply flood events and therefore wet periods, while low values imply drought events and dry periods where precipitation is relatively absent. The relation of our interest, in this case, shows a direct relationship between low SPEI and SPI values (namely dry periods), and a visible reduction in NTL values observed in the urban areas near the dams. In figure 9, the correlation between SPEI6- and NTL values are visualized over a multi-panel graph with the country-specific correlation coefficient, calculated based on each dam present in their own national territory. The stars represent the p-value attributed to each correlation that attests to the level of statistical significance. The negative correlation under the 0 represents a decreased NTL radiance level in periods of flood events.

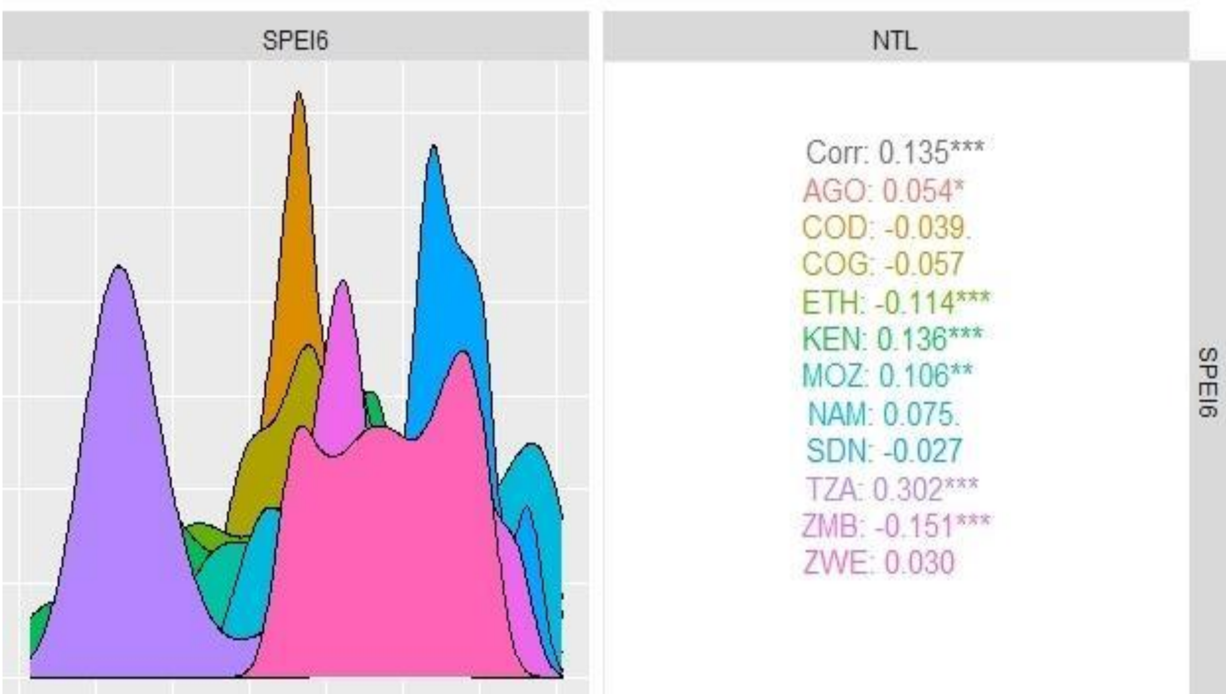


Figure 9: Multi-panel with density (top-left and bottom-right) and scatterplot (bottom-left) of Spei6- values and NTL level across the region, with a panel of correlation values (top-right).

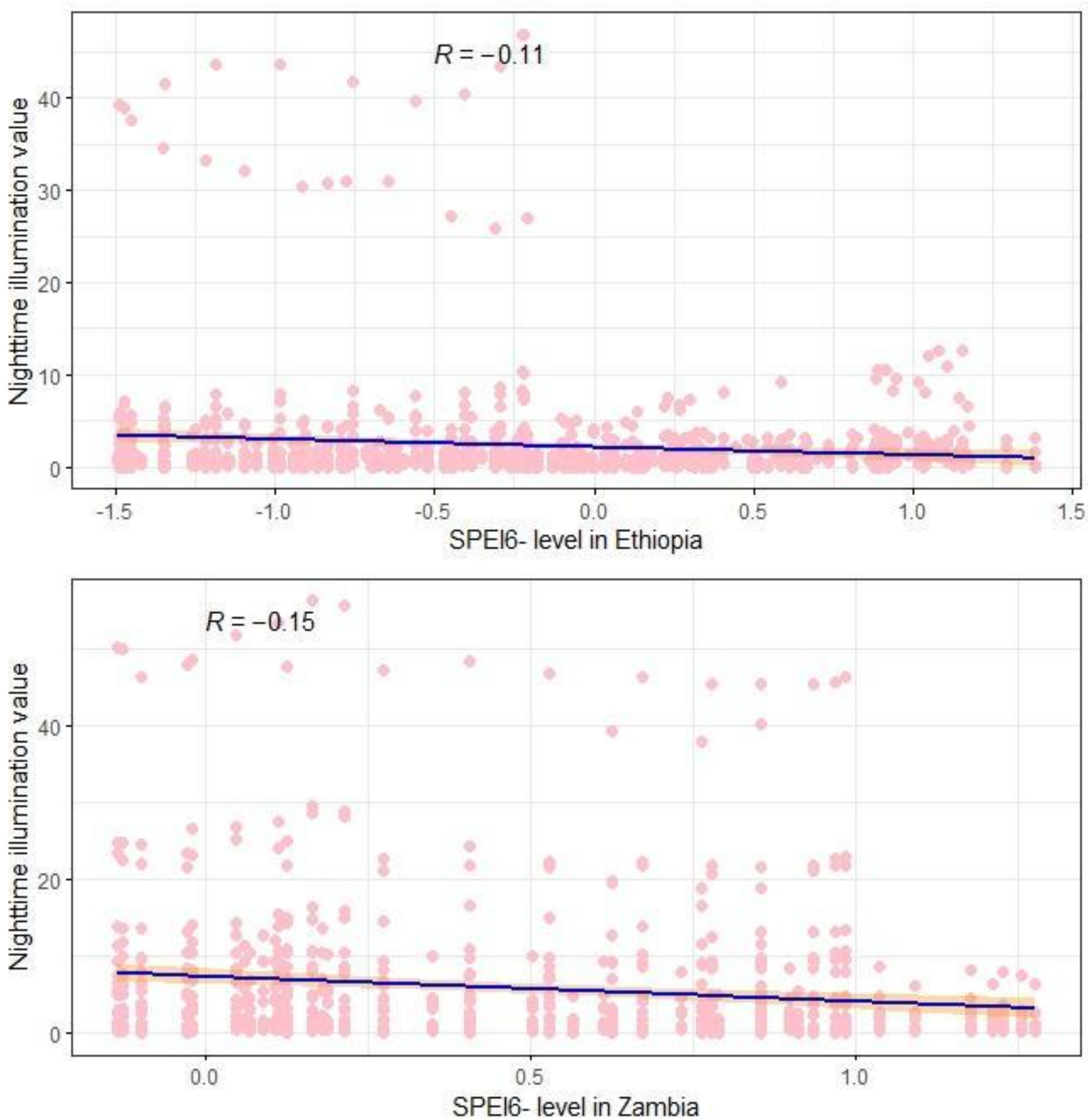


Figure 10: Scatterplot representing the correlation coefficient and the regression line between NTL and SPEI6- values in Ethiopia and Zambia

The multi-panel offered in figure 9 suggests a quite diverse situation for all the countries involved in this thesis. The highest correlation coefficients are found in the United Republic of Tanzania, Mozambique, Kenya, Ethiopia, and Zambia. The correlation is always positive apart from Ethiopia and Zambia, which show a negative correlation. A separate scatterplot for the two countries is offered in Figure 10, to visualize the implications of the negative correlations.

Overall, both countries show a statistically significant vulnerability to extreme climatic events in their energy supply. However, the negative correlation represented also by the regression line in figure 10, suggests a marked vulnerability to flooding events rather than drought episodes. This may be due to a wide array of reasons which is not possible to exactly pinpoint with the resources offered in this thesis. The scientific literature already expressed how increased precipitations in some regions will imply greater efficiency in hydropower electricity generation. However, as seen in this case, flooding events may also imply reduced generation due to flood-control purposes, debris blocking the turbines, or general structural reasons (Hauenstein, 2005).[cccxii][cccxiii][cccxiv] Ethiopia, as seen in the IPCC is expected to see its wet season increase both in duration and intensity due to climate change (IPCC, 2013).[cccxv] These results do not exclude a statistical significance of extreme events impacts over a generation. The majority of the dams present on the Ethiopian territory are conventional large dams, with only three Run-of-river power plants, logically reducing electricity supply vulnerability from short- and medium-term dry spells. Furthermore, geothermal, wind power and solar PV generation also showed a marked increase in the years considered in this work in Ethiopia. Finally, the results do not keep into account the massive increase in electricity generation from 2.54 TWh in 2004 to 8.72 TWh in 2013.[cccxvi] While still far from achieving universal electrification, in less than 10 years Ethiopia increased its capacity generation by 243%. These findings influence the final results, which depicts Ethiopian energy supply as more vulnerable to an excess of precipitation, rather than scarcity. Both climate extremes concerning drought and flooding events can be responsible for a marked decrease in hydropower generation. Flooding events may influence both RoR and reservoir dams' generation capacity, due to different technical and environmental reasons, causing up to 14% reduced hydropower generation due to flood control according to a recent study from Yun et al (2021).[cccxvii] RoR power units are forced to shut down production due to increased sedimentation from high rainfall patterns, which results in speeding up turbine abrasion, reducing sensibly the number of hours of power plant operation. Thus, the energy efficiency of the whole country, due to high reliance on hydropower, shows a structural vulnerability that has to be addressed with proper planning to address these considerations in order to achieve a more solid national energy security.

Concerning the nations with positive correlation coefficients, the United Republic of Tanzania, Mozambique, and Kenya show the highest correlation. Tanzania shows the highest correlation between drought events and reduced energy supply, with a correlation coefficient rounded at R=0.3 and a statistically significant p-value. Mozambique and Kenya have a correlation coefficient of R=0.14 and 0.11 with both holding a statistically significant p-value. Figure 11 presents a similar visual representation to that already presented for Zambia and Ethiopia, for the aforementioned three countries in figure 10. The other countries witness low correlation and statistical significance in their values, which does not justify any particular form of a causal relationship between drought events and NTL radiance levels at the 6- months timescale. However, changing the scale of the SPEI results in a different observation, with Angola showing a positive correlation (although small with R=0.054) at the 3-months SPEI timescale, and Namibia showing particularly strong results with the longer timescale of 12-months SPEI (R=0.097).

All in all, the considerations made up to now focused on the SPEI drought index. Due to the previously mentioned different nature of the two drought measurement indexes, differences between them were expected. In Figure 12 the same multi-panel correlation plot as that of Figure 9 is provided for the SPI 6- index in correlation to the NTL values.

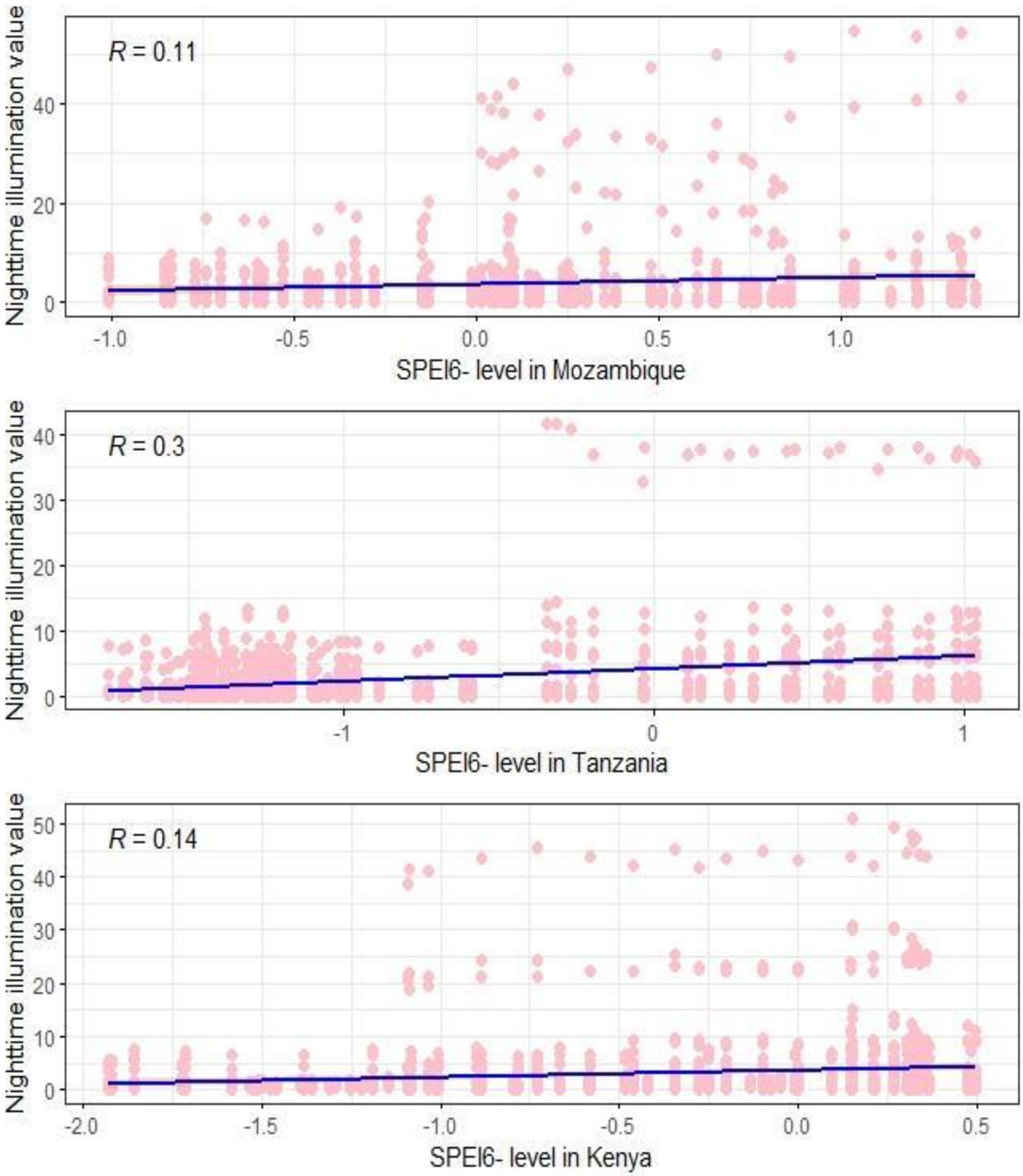


Figure 11: Scatterplot representing the correlation coefficient and the regression line between NTL and SPEI 6 values for Mozambique, Kenya, and Tanzania

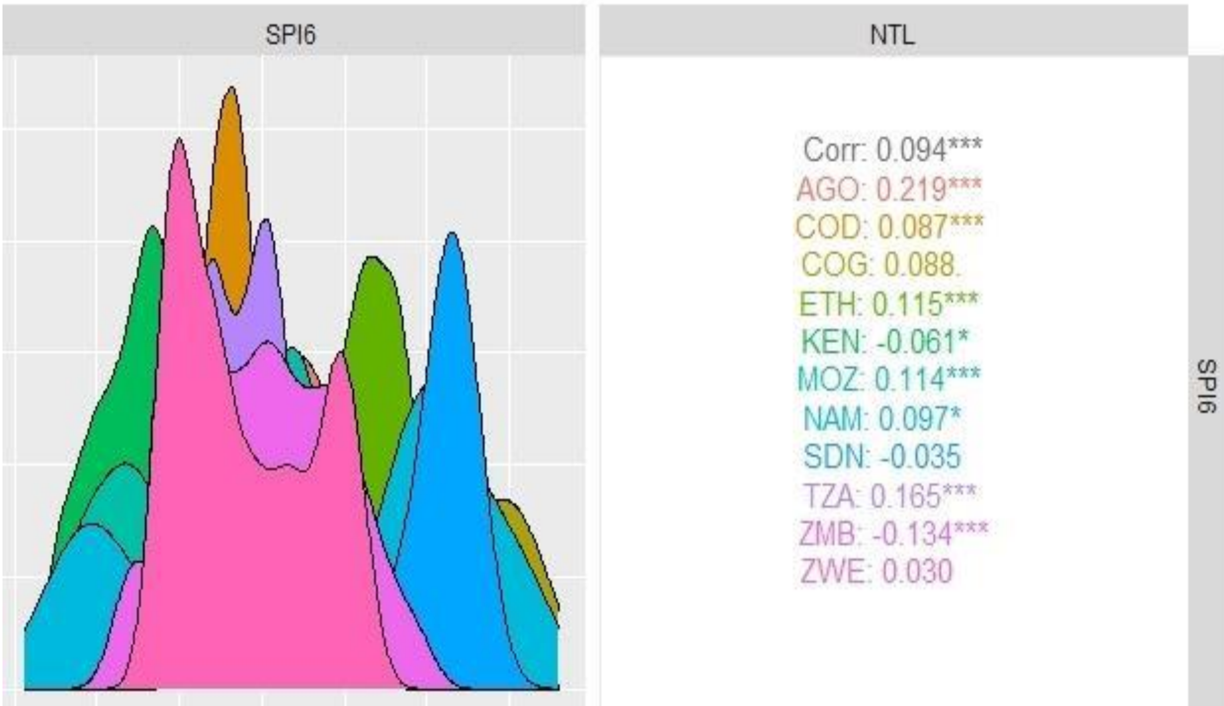


Figure 12: Multi-panel with density (top-left and bottom-right) and scatterplot (bottom-left) of Spi6- values and NTL level across the region, with a panel of correlation values (top-right).

Figure 12 visually represents the intensity of drought events measured by the SPI in correlation to the NTL levels. A positive correlation of 0.094 is found for the panel countries, with high statistical significance for all countries except the Republic of Congo, Sudan, and Zimbabwe. Sudan and the Republic of Congo both find a positive correlation with a p-value under 0.05 at a different timescale of the SPI index to 3- and 12- months, as reported in Figure 7 (although statistical significance expressed by the p-value is not as notable as other examples). In general, the reduced impact of water scarcity in the Republic of Congo may be explained by the consistent increase in their share of electricity generation from natural gas, which grew considerably from 57 GWh to 738 GWh per year.[cccxviii] This may have had a mitigation effect, reducing overreliance on hydropower and increasing the reliability of the overall energy supply in urban areas.[cccxix]

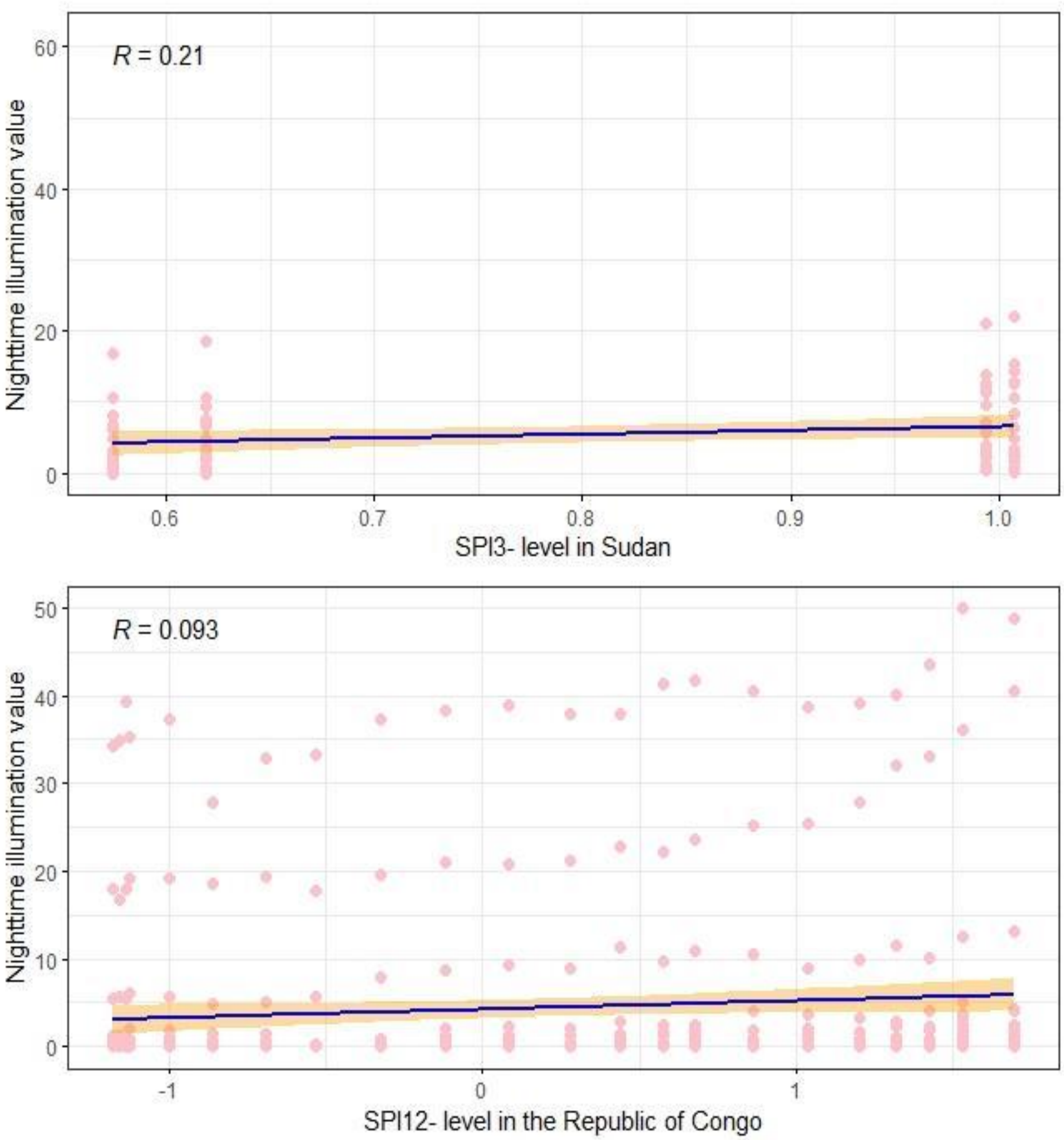
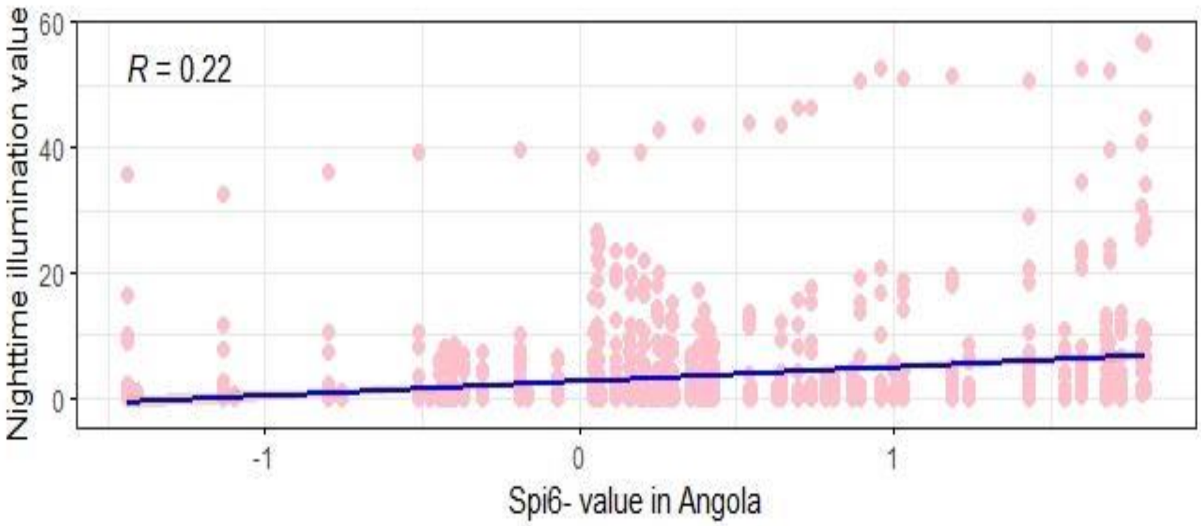
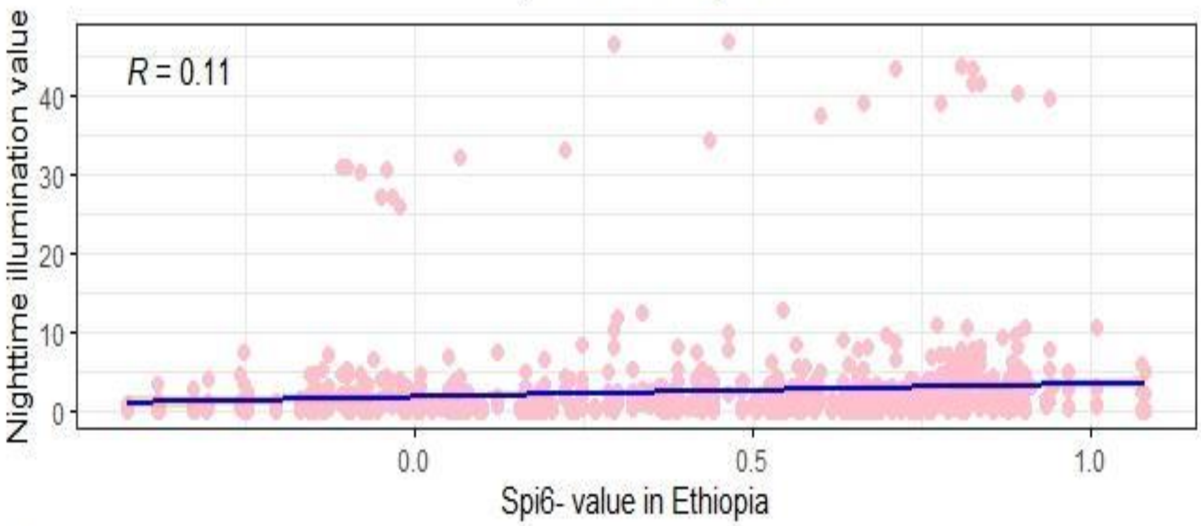
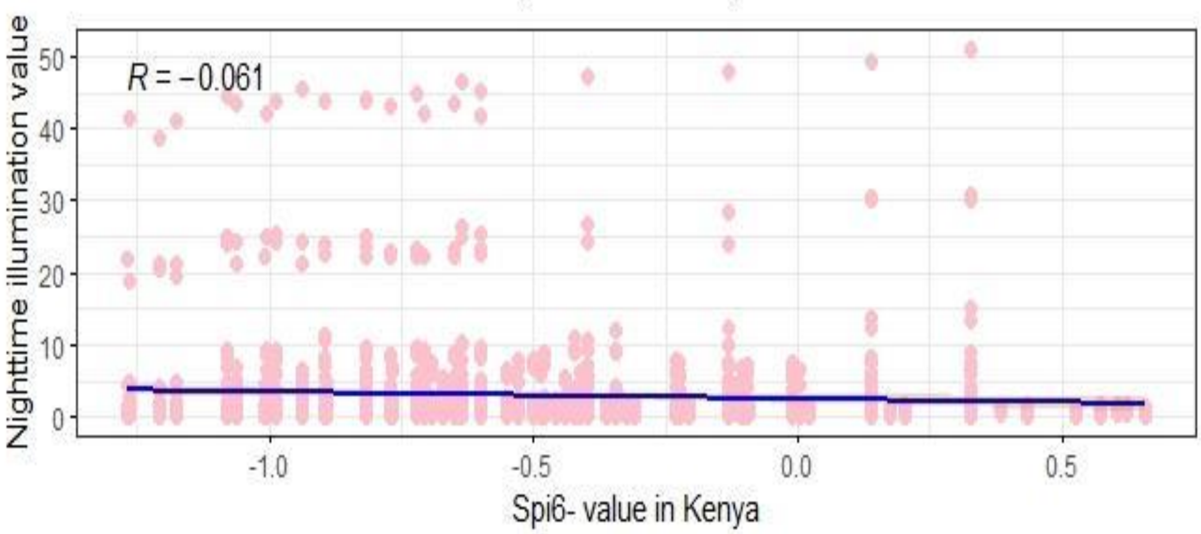


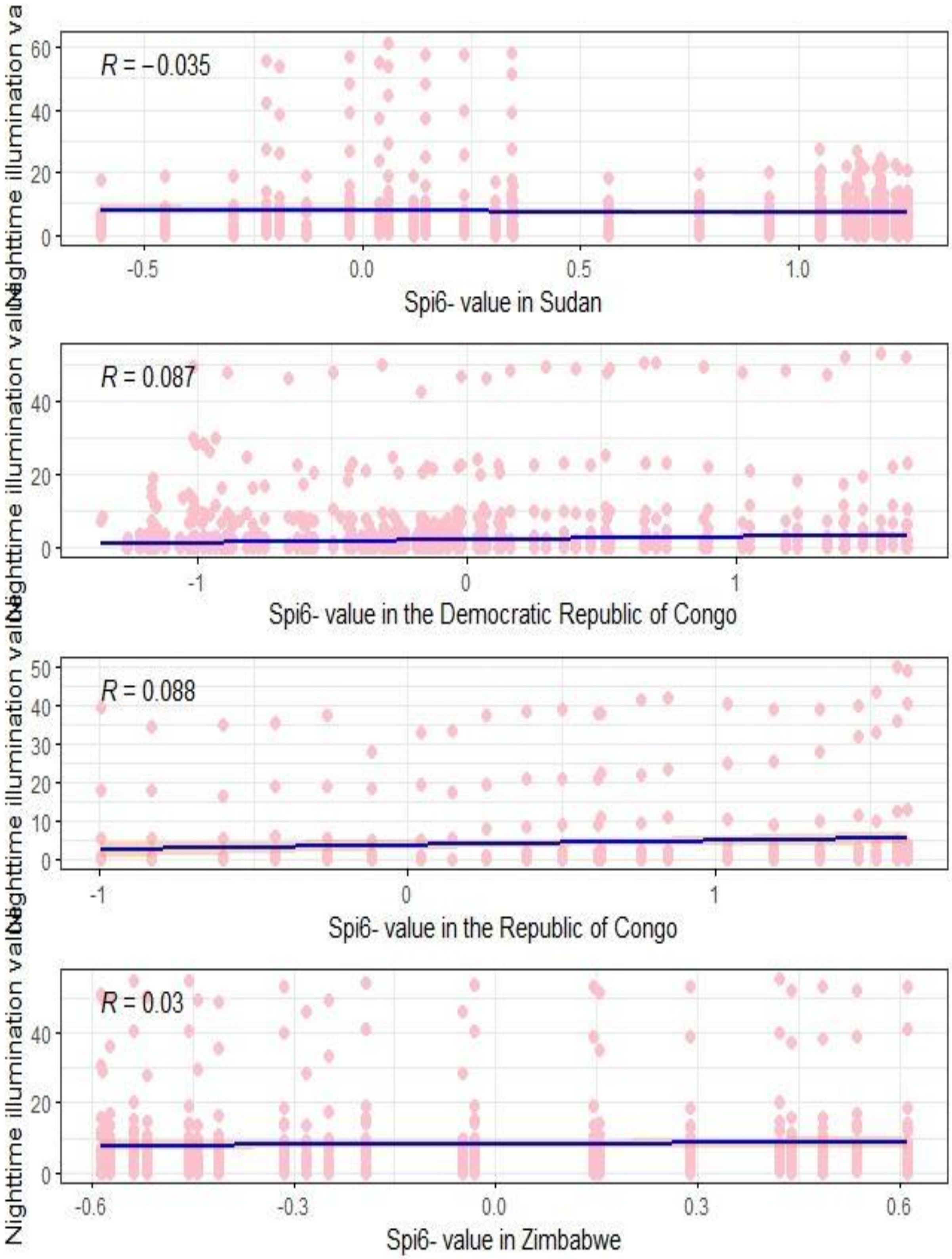
Figure 13: Scatterplot representing the correlation coefficient and the regression line between NTL and SPI3 and SPI12 index respectively in Sudan and the Republic of Congo.

As seen in Figure 13, almost every country has a positive correlation and solid statistical significance. SPI index seems particularly efficient in the 3 and 12-months time-scale, where the correlation coefficient is R=0.1 on both occasions. In conclusion, a collection of scatterplots indicating all countries' correlation coefficients with SPI6- is provided in Figures 14-15-16.


R = 0.22
Nighttime illumination value
0
20
40
60
-1
0
1
Spi6- value in Angola


R = 0.11
Nighttime illumination value
0
10
20
30
40
0.0
0.5
1.0
Spi6- value in Ethiopia


R = −0.061
Nighttime illumination value
0
10
20
30
40
50
-1.0
-0.5
0.0
0.5
Spi6- value in Kenya


R = −0.035
Spi6- value in Sudan
R = 0.087
Spi6- value in the Democratic Republic of Congo
R = 0.088
Spi6- value in the Republic of Congo
R = 0.03
Spi6- value in Zimbabwe
Nighttime illumination value

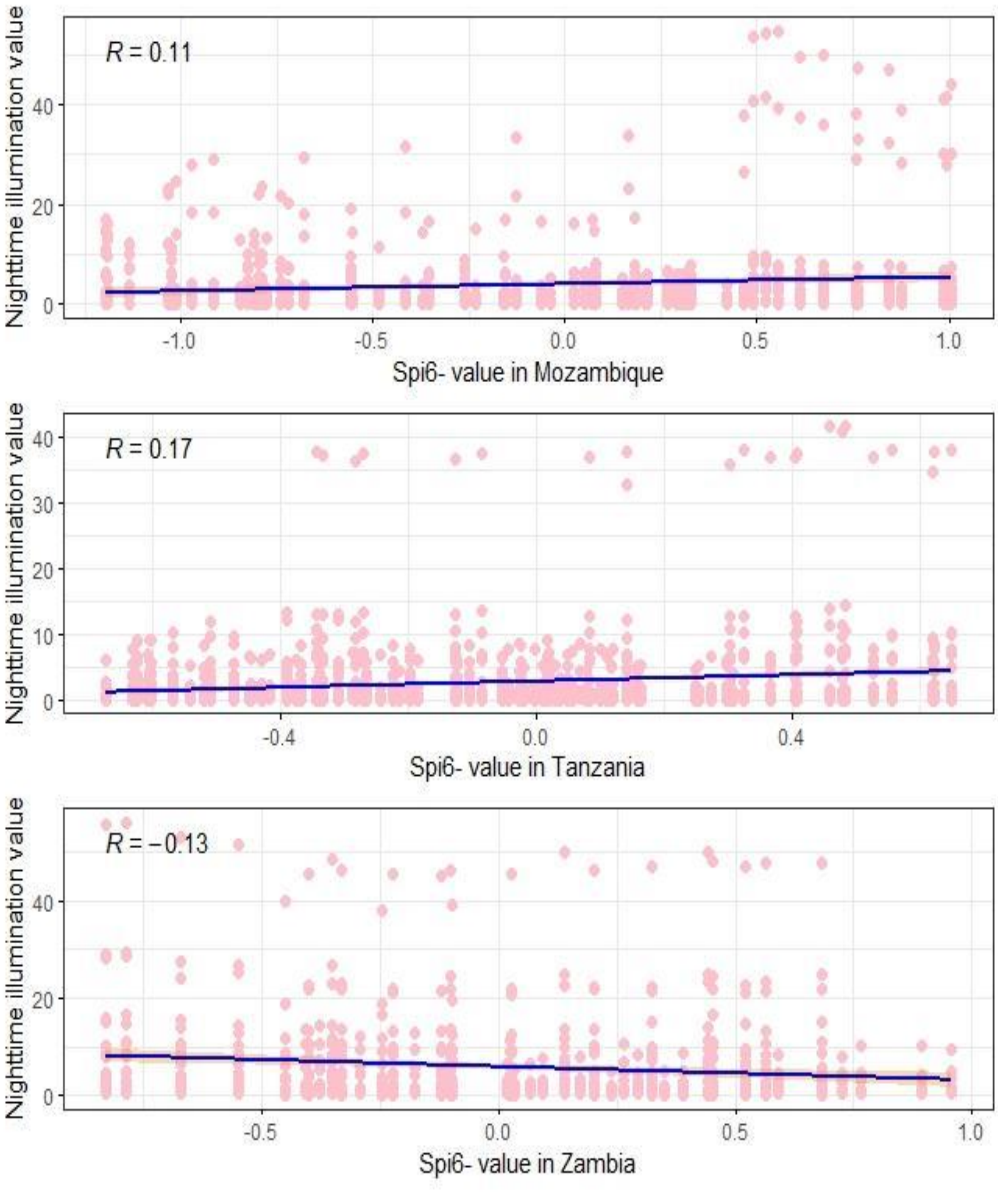


Figure 14-16: Scatterplot representing the correlation coefficient and the regression line for each specific country at SPI 6 value. Source: Own contribution

The SPI index at different timescales seems able to detect more frequent correlation and statistical significance compared to the SPEI, although with a lower correlation coefficient. This may be explained by the fact that focusing on precipitation and the fact that dams require a constant water input, the SPI detects easily the frequency of the drought events and the reduced electricity supply from nighttime illumination radiance levels. Instead, the SPEI has an overall higher correlation coefficient overall, which may be clearly motivated by the accounting for evapotranspiration in the overall index, which thus suggests the important role of temperature and evaporation as predictors in the reduced efficiency and overall power generation of dams.

Figure 18 and Figure 19 below represent the SPI6 and SPEI6 average values in the course of the 22 years of reference between 1992-2013, for each country (defined by its ISO3 code). The values represented explicitly explain how different the climatic conditions for each sub-Saharan country have been during the timespan accounted for, and how intense the drought phenomena in this region can often be. These results are visibly different, showing how accounting for evapotranspiration creates a completely different representation of the climatic conditions of certain areas. These ridges represent the specific locations of the reservoirs considered in the thesis and their SPI and SPEI values, indicating the increased frequency of an event with the height of the ridge. Both graphs are quite diverse, with some countries showing opposite numbers. Areas over Zimbabwean reservoirs are consistently dryer in the SPI6 index than compared to the SPEI6, with the same being true for Zambia, Mozambique, and Sudan. Kenya and Tanzania are particularly subject to drought events with a moderate frequency of negative values in both indexes, all in all, the most 'diverse' and balanced countries with equally spread positive and negative values in both indexes are Ethiopia, Sudan, and Namibia. SPI6 shows consistently drier periods in Angola and reports a direct correlation with the NTL values as seen in Figure 12, compared to the SPEI where overall wetter climate shows scarce correlation to NTL values of the same period. Finally, values and correlation coefficients for Tanzania, Kenya, Mozambique, and Zambia remain consistent in both indexes. Ethiopia is negatively correlated in the SPEI6-and positively correlated in the SPI6. Angola is strongly correlated in the SPI6 and just slightly in the SPEI6, and the same is shown for the Democratic Republic of Congo. All in all, only Zimbabwe, Sudan, and the Republic of Congo show low correlation and statistical significance for almost every timescale and drought-index tested, with Zimbabwe being tested over only one dam due to the criteria discussed in the last paragraph, which greatly limited the results. Sudan dams are found on the Nile, which receives consistent amounts of water from both the Blue Nile and the White Nile, thus limiting the effects of intra-seasonal droughts. In conclusion, a statistically significant correlation in 8 out of 11 countries selected as a case study, shows how drought-events measured with SPEI and SPI drought indexes, are efficient and reliable predictor variables in order to determine the energy consumption in the urban centers of sub-Saharan Africa. The results are also consistent with real-life results provided for Tanzania and Kenya. Finally, Figure 17 expresses the yearly average of the region for the SPEI 6 values, in correlation to the NTL radiance levels. This shows how the most recent years show the highest correlation to extreme events, thus suggesting the growing vulnerability of these countries to drought (or flood) events.

To conclude, Figure 20 provides a visual representation over the sub-Saharan political map, of the average precipitation levels in the region with the inter-annual mean expressed in mm/month of rainfall. The golden points represented are the hydropower plants kept into consideration for this thesis, which helps to visualize the results obtained in this correlation. Tanzanian and Kenyan dams are visibly in average dryer areas compared to Ethiopian dams, in agreement with the results of positive (thus reduced NTL values during dry periods) and negative (reduced NTL values in wet periods) correlation for these countries. In light of this diverse data, we can see how drought events still play a fundamental role in the energy efficiency of these countries. Different factors may also worsen the overall situation of energy poverty, increasing stress on water resources, for example, agricultural use during dry periods, or increased electricity consumption for thermal discomfort during periods with high temperatures (Falchetta and Mistry, 2021).[cccxx] Further discussion on the topic is obviously required in order to give a definitive answer about how much is hydropower electricity generation impacted by climatic events in sub-Saharan Africa. Still, the lessons learned, and the evidence brought using meteorological and high-precision nighttime illumination data, seem to confirm the trend observed until now in other parts of the world. While flood events become effectively less of a threat thanks to large conventional dams, they still reduce the efficiency of the energy supply. This structural situation of induced energy poverty and water scarcity, requires better political planning from policy-makers, especially in consideration of the future climatic trends. Hydropower remains an incredibly useful green technology for energy generation which plays a fundamental role in the decarbonization effort of the whole world, but over-reliance on hydroelectricity entails risks linked to reduced precipitation and increased evaporation which have already visible impacts in some parts of the world. These issues need to be addressed from the planning phase and need to account for both meteorological and climatic structural conditions if the objective of ending energy poverty in the developing world is to be achieved.

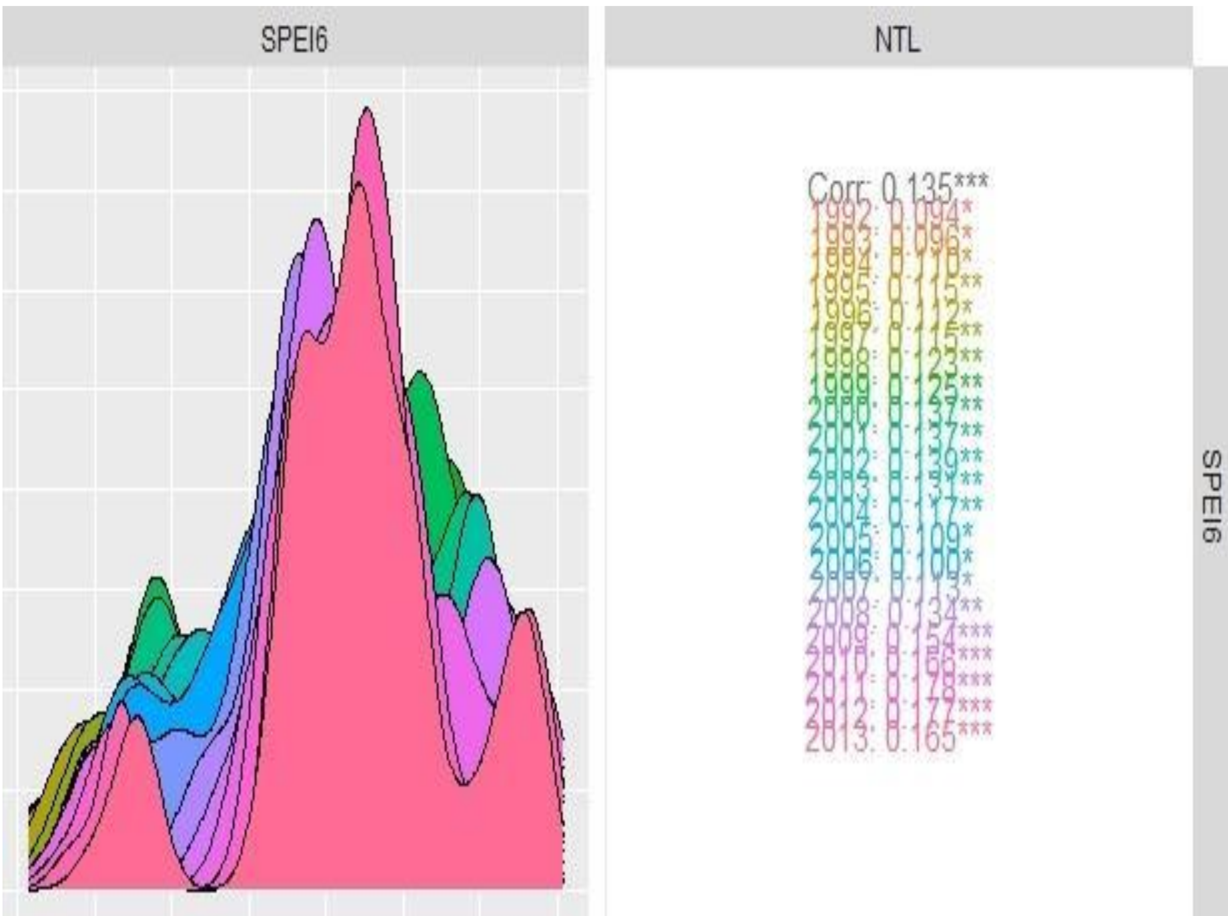


Figure 17: Correlation between SPEI 6 and NTL values throughout the 22 years of reference. Source: Own contribution

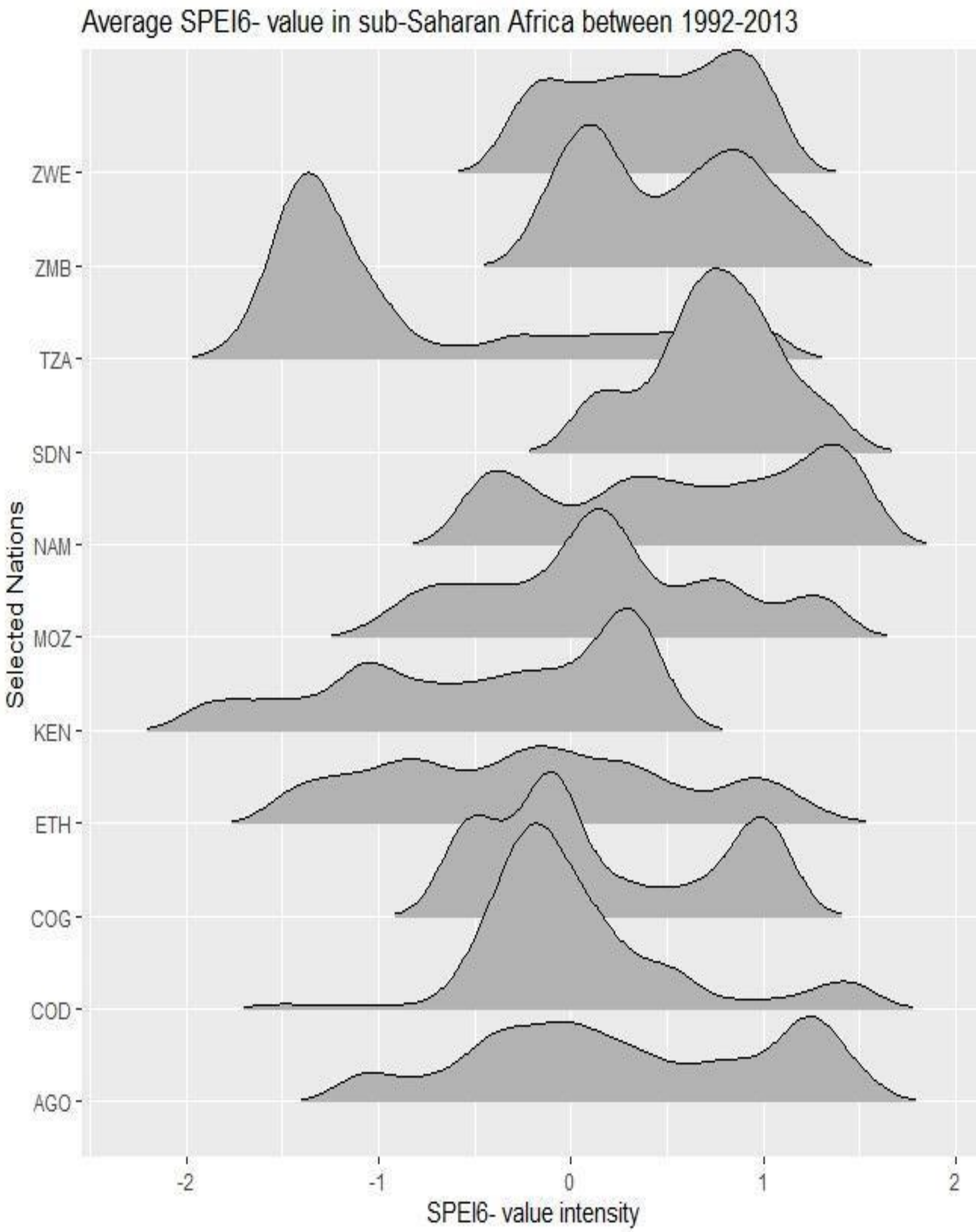


Figure 18: Distribution of SPEI6- index values for all the selected nations between 1992-2013. Source: Own contribution based on the data listed in Chapter 3.

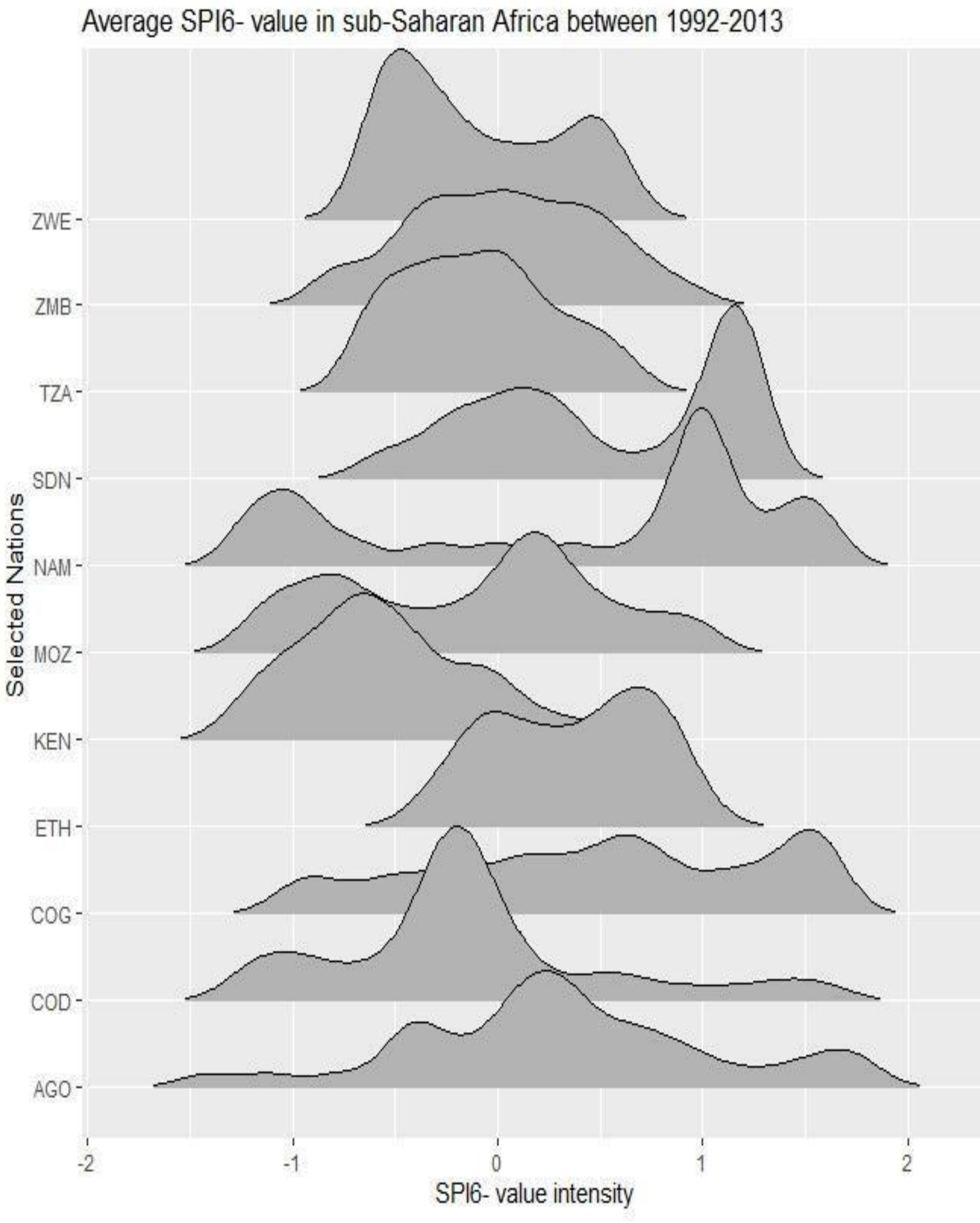


Figure 19: Distribution of SPI6- index values for all the selected nations between 1992-2013. Source: Own contribution based on the data listed in Chapter 3.

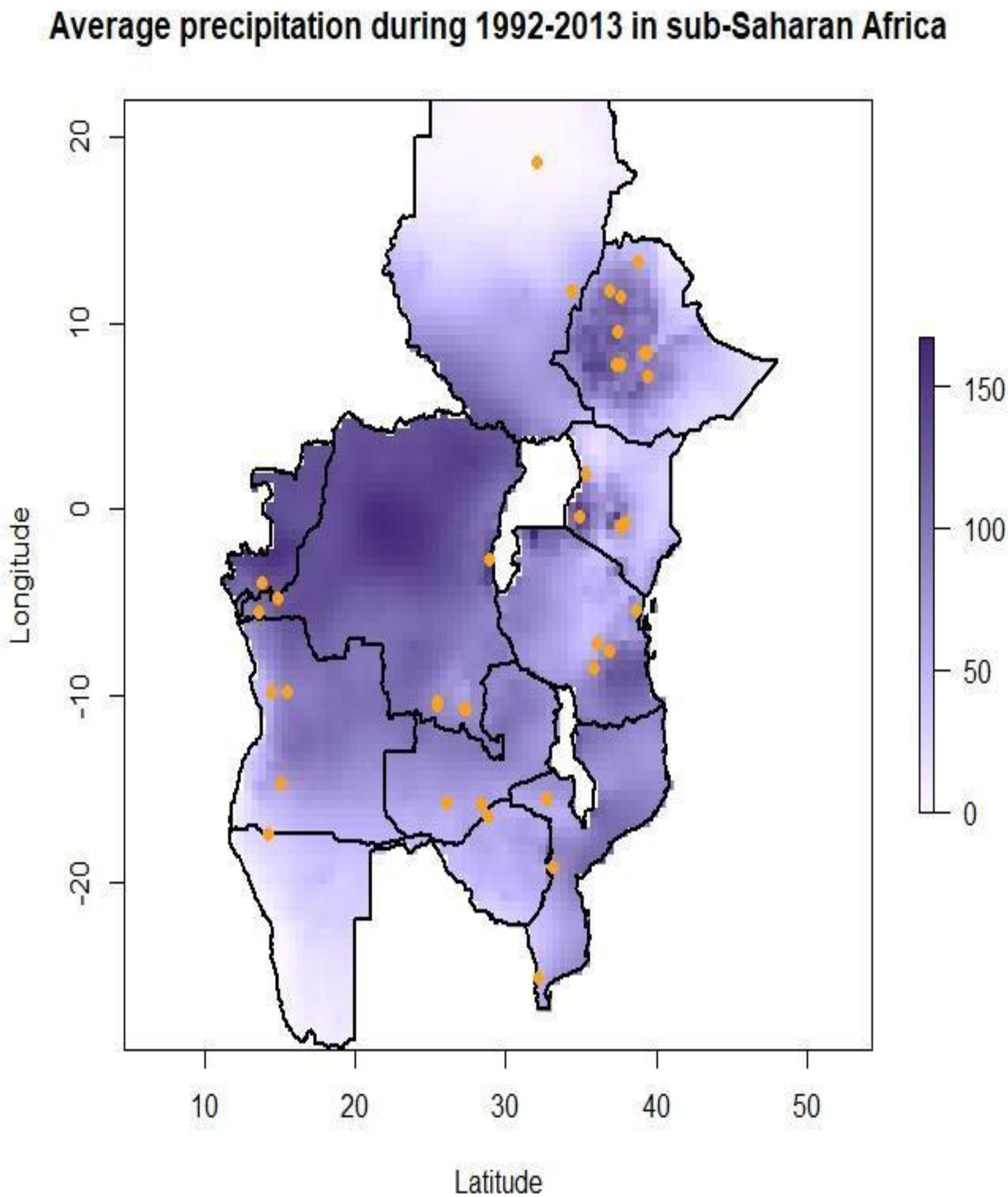


Figure 20: Political map of sub-Saharan African countries selected, representing the average precipitation levels in mm/months of rain between 1992-2013, and the selected dam locations (orange points). Source: Own contribution based on the data listed in Chapter 3.

5. Discussion and Conclusions

Too large a proportion of recent "mathematical" economics are mere concoctions, as imprecise as the initial assumptions they rest on, which allow the author to lose sight of the complexities and interdependencies of the real world in a maze of pretentious and unhelpful symbols.
Cit. John Maynard Keynes

Too often the existing research concerning hydropower tends to focus on either the positive or negative direct aspects of this source of energy. In both the first and second chapters, however, the evidence gathered through secondary and primary (?) data and literature highlights how direct and indirect aspects often co-exist and determine the choice to rely on hydropower. The Water-Energy nexus framework makes it possible to develop a comprehensive discussion around this topic. The debate on hydropower may be presented with several different perspectives and discussed within several social and environmental sciences sectors. Within the framework of the Water-Energy nexus, the discussion on hydropower highlighted the main literature concerning different aspects of human security. Evidence of the relation between dam-building and human conflict has been provided at the regional (by resettling villages or increasing water competition) and international (as a military and terrorist objective or as a source of political tensions) levels. Social tensions are generated due to a variety of reasons that often trigger security concerns at the international level. This security approach has been frequently witnessed in different transboundary river basins, but it must not represent a deterministic truth. Cooperative management of river basins has been achieved in some regions and has been theoretically examined in many other basins prone to this kind of conflict as a ‘benefit multiplier’ instead of a threat. This is however extremely dependent on the diverse political and diplomatic aspects that each country, when building a large conventional dam, decides to pursue.

A small review concerning climate change was factored in. The evidence collected, clearly pointed towards a decisive increase in intensity, magnitude, and frequency of droughts. In particular, sub-Saharan Africa is expected to witness a dryer climate in dry regions, and a wetter climate in wet regions. This proves to be particularly dangerous for the structural conditions presented in the region, where water infrastructure is severely lacking, and agriculture is the main economic activity. This provides some perspective on the possible risks for Run of the River power plants, which are reliant on constant water inputs, but also the advantages provided by the construction of reservoirs that result in increased water capacity. Furthermore, increasing the electricity generation capacity provides enormous benefits on the social and economic side. These benefits usually mitigate the political tensions generated by dam-building by exporting the electricity generated to countries downstream, as seen in Ethiopia and Kenya. All in all, this cheap and renewable energy has a positive interaction with the global investment agenda of international institutions like the UN initiatives and the World Bank.

Following, in the second Chapter, specific evidence is digested and focused towards sub-Saharan specific conditions. The evidence is focused on region-specific environmental impacts, socio-economic structural conditions, and the particular climate conditions present. Factoring in these specific conditions in the previously discussed literature outlines a variety of vulnerabilities affecting the region, and the close interactions, whether positive or negative, that dams reservoirs generate. All in all, the nexus approach is extremely efficient in providing a deep analysis of the ramifications of risks and benefits of hydropower. Furthermore, the climate is a particularly decisive influencing factor for the water-energy systems, particularly so in a region lacking appropriate water and energy infrastructure to mitigate extreme events. Properly addressing droughts and flood events with an efficient infrastructure system and management would greatly benefit the socio-economic conditions of the local population, producing a possible spillover in other regions or in other sectors.

In light of the literary evidence related to the interaction of the regional climate system over the water and energy systems, the third and fourth chapters attempt a quantitative analysis of the interaction discussed. In consideration of the high dependence on water input of the sub-Saharan Africa energy system, and the widespread lack or low quality of reliable data, remote-sensed satellite-based data is used to observe whether a correlation between drought events and electricity supply exists.

Scholars have long pointed out how the lack of information and data-sharing technologies are strong hampering factors of socio-economic progress in Africa (Jerven, 2013; Hoogeven and Pape, 2020). While lacking the precision necessary to give a perfect estimate of the issue at hand, remote-sensed data proved effective in finding a statistically relevant correlation. The different timescales of the SPEI and SPEI index show growing relations throughout the years between

1992 and 2013. This increasing correlation visible in Figure 18, is justified by the various investments in increasing hydropower generation capacity in the early 2000. During these years however, Tanzania and Kenya reported severe reductions in electricity supply due to drought events and water scarcity, therefore started diversifying their energy mix with other generating technology. The efficiency of this diversification process, however, strongly relies on thermoelectrical power, which has been proved to be also vulnerable to drought events. Other nations, as seen with the Democratic Republic of Congo and Ethiopia, chose to increase their generation capacity to face the ongoing electrification effort, with an increase in hydropower capacity due to cost efficiency and the consistent untapped potential.

In light of the present correlation and of the empirical evidence on the future impacts of climate change, a diversification of the energy mix to other sources non-reliant on water inputs might provide the best results. The most recent future estimates forecast an increase in drought events duration and intensity due to climate change in the coming years. In correspondence with the present results, the statistical correlation found is expected to increase with the intensification of climate change impacts. This would not be particularly impactful for the energy system, but for all the different perspectives and sectors approached in the first part of this thesis and that are, directly or indirectly, influenced by water and energy scarcity. Thus, a consistent diversification of the energy mix might start by untapping the solar, wind, and geothermal potential present in different countries among the selected ones. Finally, an important tool to counter the growing impacts from increased temperatures, would be offered by strengthening the electricity market between the nations in the region. This extended market may effectively counterbalance the threat posed to the energy system by a trans-regional phenomenon such as that of drought events. With the world growing closer and closer each day, threatened by climate change, policymakers have a once-in-a-time opportunity to create a more cooperative and peaceful society, in order to mitigate the impacts from an increase in temperature. In case of inaction, the interlinkages between conflict and scarcity of resources provided in the first chapter, will likely result in a future plagued by chaos and conflict.

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