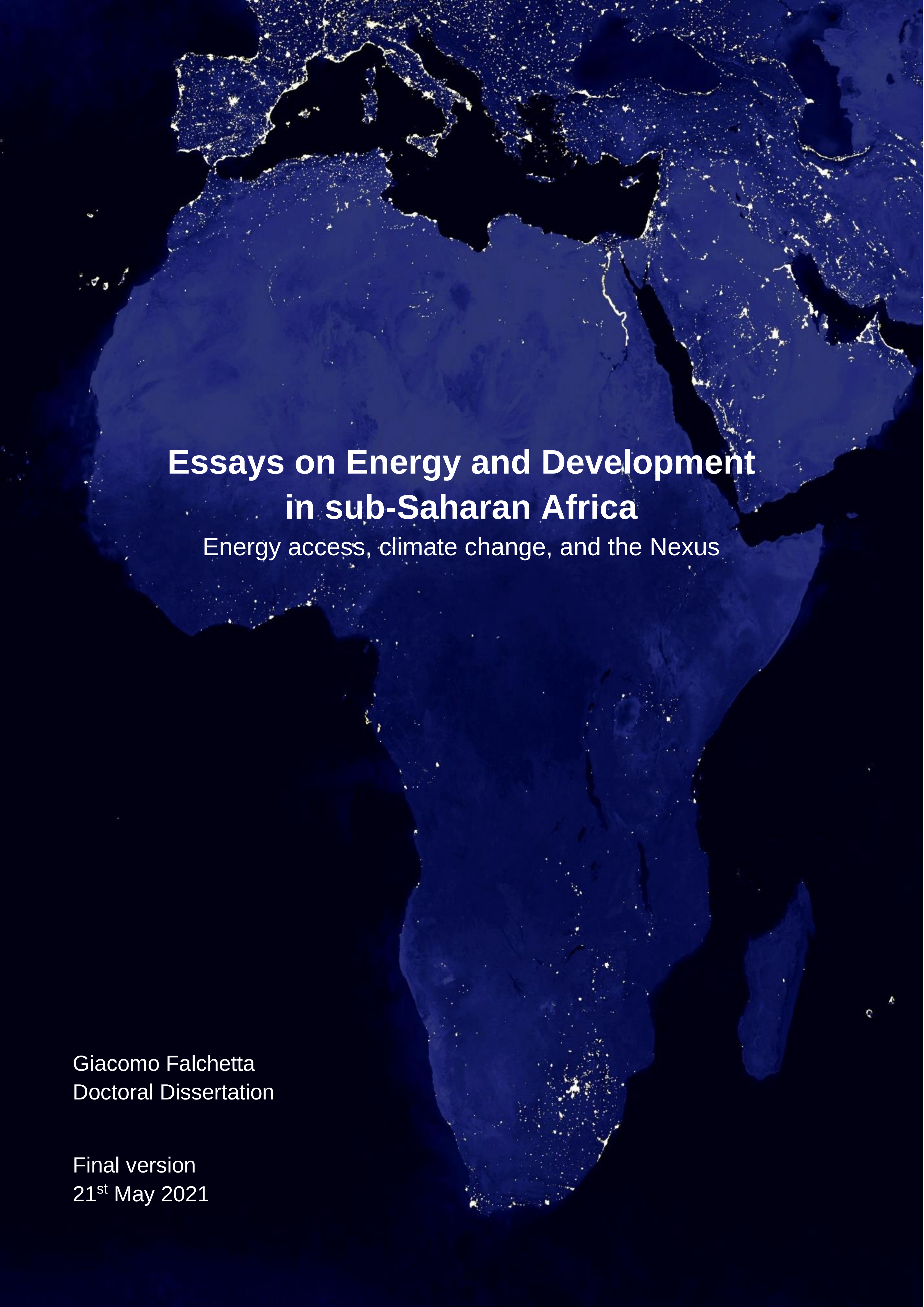

Essays on Energy and Development in sub-Saharan Africa

Energy access, climate change, and the Nexus

Giacomo Falchetta
Doctoral Dissertation

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Essays on Energy and Development in sub-Saharan Africa

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Cover picture: NASA Black Marble (Earth at Night 2016)

“*Saving our planet, lifting people out of poverty, advancing economic growth... these are one and the same fight. We must connect the dots between climate change, water scarcity, energy shortages, global health, food security and women’s empowerment. Solutions to one problem must be solutions for all.”*

Ban Ki-moon

Former Secretary-General of the United Nations

Essays on Energy and Development in sub-Saharan Africa

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Abstract

This dissertation is a collection of five essays examining some important energy-related aspects at the interplay of sub-Saharan Africa (SSA)'s development and its interactions with the regional and global environment. The essays are introduced by a **general overview chapter** – highlighting the core energy-related challenges of SSA and the scope of this work. The main implications of the essays, both for research and for policymakers, are then considered in the **final discussion chapter**.

The **first essay** focuses on access to modern energy, and chiefly on electricity. I illustrate the role of satellite data and the statistical analysis of geospatial data in improving the understanding of the electricity access situation in sub-Saharan Africa. The essay includes an analysis of inequality characterising the electricity access quality in the region. The main finding is that after decades, energy access inequality is beginning to decline but it remains prominent in particular as far as the quantity consumed is concerned. I find that electrification efforts between 2020 and 2030 must triplicate their pace to meet Sustainable Development Goal 7.1.1.

The **second essay** develops a spatially-explicit bottom-up energy demand assessment platform to estimate the energy needs among communities where access to electricity is currently lacking, as identified with the methodology introduced in the first essay. The assessment is not restricted to residential energy needs, but it includes a detailed, appliance-based account of power needs for schools, healthcare facilities, water pumping for irrigation, crop processing, and micro enterprises, the key drivers of rural development. I carry out a country-study for Kenya to show the importance of considering multiple demand sources beyond residential when the aim is developing an electrification strategy which truly overcomes energy poverty. I also show that there is considerable potential for rural productivity and profitability growth thanks to the input of electric energy. In many areas, these local profits might pay back the electrification infrastructure investment in only few years.

The **third essay** analyses a specific aspect at the interplay between electricity access planning, household energy demand and climate change adaptation. I

combine climate, satellite, and demographic data and scenarios to produce a global spatially-explicit estimate of unmet ACC demand due to the lack of electricity access. Based on integrated climate-energy and geospatial electrification modelling, I find that in sub-Saharan Africa, the global hotspot of energy poverty, accounting for the estimated local ACC needs on top of baseline residential consumption targets determines a substantial reduction in the share of decentralised systems as the least-cost electrification option by 2030, and a major ramp-up in the power generation capacity and investment requirements. My results call for a greater consideration of climate adaptation needs in the planning of energy systems of developing countries and in evaluating the trade-off between the central power grid expansion and decentralised systems to achieve universal electrification.

Electrification planning must be techno-economically efficient, but it must also consider the political-economic environment where investment needs to be channelled. The **fourth essay** evaluates the role of governance and regulatory quality in the electricity access modelling framework. In particular, I introduce an Electricity Access Governance Index based on multiple indicators implement it into the PBL’s IMAGE-TIMER electrification model through its modifier effect on private discount rates (a measure of risk and willingness to accept future costs vis-à-vis present costs). The results show that governance and regulatory quality in electricity access have a significant impact on the optimal technological mix and the private investment flows for reaching universal electrification in sub-Saharan Africa. In particular, risky environment crowd out private providers of decentralised energy access solutions with the risk of leaving many without electricity even after 2030.

The **fifth and final essay** takes a nexus perspective in the analysis of the African power sector. It deals with the reliability of the energy system in hydropower-dominated power systems (such as in many countries in Central and East Africa) and the role that climate change and extreme events can exert on it. The essay combines qualitative and quantitative analysis to (i) propose a robust framework to highlight the interdependencies between hydropower, water availability, and climate change, (ii) systematically review the state-of-the art literature on the projected impacts of climate change on hydropower in sub-Saharan Africa, and (iii) provide supporting evidence on past trends and current pathways of power mix diversification, drought incidence, and climate change projections. I find that climate change can affect supply reliability and security in multiple ways. For instance, several major river basins have been drying throughout the twentieth century. Nonetheless, I highlight that diversification has hitherto only been promoted in a limited number of countries. I suggest how integrating variable renewables and hydropower can increase system resilience.

Acknowledgements

If I think about the first days as a PhD student, in 2017, I remember myself groping in the dark in front of my laptop screen, slowly realising what I was looking into. During those first months I have read a long set of papers, articles, book chapters, and attended seminars, lectures, lessons on the topic I was embarking. I had the luck of meeting fantastic and knowledgeable people who helped me embarking on the journey with their knowledge and support. My background in humanities taught me to categorise things. So, let me call this first stage that of the λόγος (logos), that is, of reasoning and knowledge.

Then, when I had a clue of what I was looking into, I wanted to do it rigorously and with up-to-date tools. I started to dig deep in methodology: I started learning coding, I became proficient in GIS analysis, and I have started understanding the technical aspects of the energy systems – such as the use energy models – which was hitherto to me obscure matter. Let me define this second stage that of the ἐπιστήμη (epistème), of the science as intelligible knowledge.

When I finally felt sufficiently comfortable with both the topics and the methods, I could finally start producing research. But, suddenly, deeper question related to the challenges rooted in the topics inquired and the points-of-view taken to analyse them faced in my mind. I like to define this third phase that of the ἦθος (ethos), i.e. of the morality, namely the motivation, the purpose.

Two drivers are behind this incredible path: the motivation I have myself kept on finding through the inquiry; and the collaboration, help, support, suggestions, and discussion with people without which my motivation alone would have been vain. Here I will try to acknowledge some of the many who made this journey possible.

The first acknowledgement goes to my supervisor, Prof. Roberto Zoboli, who supported the direction of my research and with whom I discussed academic doubts about the present and the future. Right after, I would like to thank Dr. Shonali Pachauri, the co-supervisor of this dissertation, with whom I had the luck to share collaborations and discussions about the energy access challenge and its analysis in the early stages of the PhD, which had a great impact on everything I have done since then. I gratefully acknowledge the two external reviewers who provided useful feedback to the first draft of this dissertation: Prof. Valeria Costantini and Prof. Giovanni Marin. Next, I would like to acknowledge Prof. Manfred Hafner, the program coordinator of the Future Energy Program research group at Fondazione Eni Enrico Mattei (FEEM), the research centre where I carried out the bulk of the research and through which I could benefit from additional opportunities that, together with my doctoral student status, made this path even more special.

A huge ‘thank you’ goes to all the people I have collaborated with or who truly acted as committed teachers with me, with a special mention to Michel Noussan, Olha Danylo, Edward Byers, Magda Moner-Girona, Sebastian Sterl, Simon Parkinson, Lucia de Strasser, Davide Mazzoni, Nicolò Stevanato, Nicolò Golinucci, Simone Tagliapietra, Anteneh Dagnachew, and many others.

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Collaborations

The five essays contained in this dissertation are the result of the candidate's individual work throughout the three years of duration of the Doctoral program.

Besides the time spent at the Cattolica University, work has been carried out at the following research institutions:

- Fondazione Eni Enrico Mattei, November 2017 – May 2021.
- International Institute for Applied Systems Analysis, October 2018 – March 2019
- PBL Netherlands Environmental Assessment Agency, January 2020 – March 2020

While interacting with researchers at those institutions, I have received several contributions in the form of advice, manuscript revisions, methodological discussions, and technical support. Here below I try to acknowledge – for each essay contained in this dissertation – the external contributions received. **Nevertheless, the candidate remains the sole person responsible for the work presented in this dissertation.**

- **Essay 1:**

Dr. Shonali Pachauri (International Institute for Applied Systems Analysis), Dr. Simon Parkinson (International Institute for Applied Systems Analysis) and Dr. Edward Byers (International Institute for Applied Systems Analysis) contributed to the discussions which led to the conceptualisation of the methodology and – at later stages – to the revision of the manuscript. Dr. Olha Danylo (International Institute for Applied Systems Analysis) provided technical support with geospatial data processing.

- **Essay 2:**

Prof. Manfred Hafner (Fondazione Eni Enrico Mattei) contributed in the conceptualisation stage, while Paolo Cornali (Fondazione Eni Enrico Mattei) and Nicolò Stevanato (Fondazione Eni Enrico Mattei) contributed to defining the energy modelling strategy. Useful advice was provided by Prof. Emanuela Colombo (Politecnico di Milano) and Dr. Magda Moner Girona (European Commission Joint Research Centre).

- **Essay 3:**

Dr. Shonali Pachauri and Dr. Malcolm Mistry (Ca' Foscari University of Venice) reviewed a preliminary draft of the essay and provided feedback on it.

- **Essay 4:**

Anteneh Dagnachew (PBL Netherlands Environmental Assessment Agency), Dr. Andries Hof (PBL Netherlands Environmental Assessment Agency), and David Milne (Utrecht University) contributed to the conceptualisation of the methodology through frequent discussion. Anteneh Dagnachew also provided support in operating the IMAGE-TIMER model.

- **Essay 5**

Dr. Julian David Hunt (International Institute for Applied Systems Analysis), Dr. David Gernaat (PBL Netherlands Environmental Assessment Agency), and Sebastian Sterl (Vrije Universiteit Brussel) reviewed a preliminary draft of the paper and provided useful input to improve it.

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List of frequent abbreviations

ACC: Air conditioning and cooling
Bcm: Billion cubic meter
CAPEX: Capital expenditure
CDM: Clean Development Mechanism
CDD: Cooling degree days
CH_4: Methane
CMIP5: Coupled Model Intercomparison Project - phase 5
CO_2: Carbon dioxide
CSP: Concentrated solar power
DHS: Demographic and Health Survey
DR: Discount rate
EAGI: Energy Access Governance Index
EC-JRC: European Commission Joint Research Centre
EF: Emission factor
EJ: Exajoule
ESMAP: Energy Sector Management Assistance Program
FEEM: Fondazione Eni Enrico Mattei
FAO: Food and Agriculture Organisation
GADM: Global Administrative Units
GCM: General circulation model
GDP: Gross domestic product
GEM: Geospatial Electrification Model
GHG: Greenhouse gas
GHSL: Global Human Settlement Layers
GIS: Geographical information system
GJ: Gigajoule
Gt: Gigaton
GW: Gigawatt
Ha: Hectare
HFO: Heavy-fuel-oil
HPP: Hydropower plant
HRSL: High-resolution Settlement Layers
IAM: Integrated assessment model
IEA: International Energy Agency
IIASA: International Institute for Applied Systems Analysis
IMAGE: Integrated Model to Assess the Global Environment
IPP: Independent Power Producer
IPCC: Intergovernmental Panel on Climate Change
IRENA: International Renewable Energy Agency
kW : Kilowatt
kWh: Kilowatt hour
kWp: Kilowatt peak

LCA: Life-cycle assessment
LPG: Liquefied petroleum gas
MENA: Middle East and North Africa
MESSAGE: Model of Energy Supply Systems And their General Environmental Impact
M-LED: Multi-sectoral Latent Electricity Demand Assessment tool
Mt: Megatonne
MW: Megawatt
MWh: Megawatt-hour
NDCs: Nationally Determined Contributions
NTL: Nighttime lights
OECD: Organization for Economic Co-operation and Development
OLS: Ordinary Least Squares
OPEX: Operational expenditure
PAYG: Pay-as-you-go
PBL: Netherlands Environmental Assessment Agency
PCA: Principal Component Analysis
PPP: Purchase power parity
PV: Photovoltaic
PWh: Petawatt-hour
RAMP: Rural Areas Multienergy load Profile generator model
RCPs: Representative concentration pathways
RF: Random forests
RISE: Regulatory Indexes for Sustainable Energy
RE: Renewable energy
RoR: Run-of-river
SDG: Sustainable Development Goal
SPEI: Standardized Precipitation-Evaporation Index
SRES: Special Report on Emissions Scenarios
SSA: Sub-Saharan Africa (South Africa excluded)
SSPs: Shared socio-economic pathways
TIMER: Targets IMage Energy Regional model
TPED: Total Primary Energy Demand
TPES: Total Primary Energy Supply
UNDESA: United Nations Department of Economic and Social Affairs
USAID: United States Agency for International Development
USD: US Dollars
US EIA: US Energy Information Administration
VIIRS-DNB: Visible Infrared Imaging Radiometer Suite Day-Night Band
VRE: Variable Renewable Energy
WB-MTF: World Bank Multi-Tier Framework
WEF(E): Water-energy-food-(environment)
WGI: World Governance Indicators

1. Introduction

1.1. The growing importance of sub-Saharan Africa for the global economic, environmental, and demographic pathway

During the 20th century large parts of the *'Global North'* witnessed a massive process of industrialisation and infrastructure development which led to a dramatic improvement of socio-economic conditions. In the same period, other areas of the world – a key one being sub-Saharan African (SSA) – witnessed much more marginal transformations in their economic structure and affluence levels (World Bank, 2019). In 1950 the share of SSA's population was about 7% of the global total, whilst today the figure is close to 15% (United Nations, Department of Economic and Social Affairs, 2017). Yet, the share of SSA's GDP stood relatively constant (from about 2.2% of the global total in 1961 to about 1.9% today; World Bank, 2019).

Since the beginning of the 21st century, different signals have however begun to suggest a growing relevance of the SSA economy in the global goods and services market, and therefore in the international political arena. The region is also gaining more prominent relevance in the discussions about the economic, environmental, and social pathways that the world will follow in the current century and beyond.

There are several pieces of evidence supporting the idea of a quickly growing active role of SSA in the global sphere:

- Firstly, SSA is the region in the world where the population is growing faster: today it hosts about 1.1 billion people, but middle-of-the-road projections suggest that within thirty years the region will very likely host about the double (United Nations, Department of Economic and Social Affairs, 2017), i.e. that SSA would overtake - and by far - the currently most populous countries in the world, namely China and India.

- Secondly, the urbanisation rate will also grow significantly, with projections suggesting a shift from today's 41.4% to 58.1% in 2050 (DESA, 2018). Whilst Africa's cities will be home to an additional 950 million people by 2050 (OECD and Sahel and West Africa Club, 2020), rural settlements in SSA will still be inhabited by significantly more people than they do today. Therefore, SSA will exhibit two parallel socio-demographic dimensions: on the one hand a dense, growingly industrial and wealth core; on the other, a sparse but very significant periphery where a large share of the first necessity products consumed in cities are produced and – at the same time – where dwellers still pursue subsistence and development.

- Thirdly, the region is also growing robustly from an economic point of view. Several potential new economic powers such as Kenya, Ghana, and Tanzania are quickly emerging (all growing faster than 5% per year, World Bank 2019). The region-wide growth rate is at 2.4% per year, but it is projected to accelerate dramatically. It must be however remarked that so far this growth has been highly unequal both within (with skewed distribution among population groups) and across countries (with a prominent growth in natural resource exporting or industrialising countries and, conversely, other areas still stagnating).

Whilst necessary, economic growth is however insufficient for increasing local well-being and ensuring development for everyone. Diffused well-being requires access to secure and reliable services, including healthcare, education, safe and reliable energy, a job market, business opportunities, and all those assets which people in higher income regions consider guaranteed in their lives. As a result of the unequal economic growth (both between and within countries) *vis-à-vis* a relatively more homogeneous demographic growth, most social indicators of the quality of life - such as those designed by the targets of each Sustainable Development Goal (United Nations, 2015) - are the lowest in the world in most countries of SSA, and in some instances the situation is even deteriorating, with little or very unequal progress.

In addition, a quick and unequal socio-economic development coupled with a growing population demanding good and services is likely to translate into a growing pressure on the environment. Energy – the core resource assessed in this dissertation – is one of the most crucial determinants of both development opportunities and environmental impact at different scales (see §1.2). Other crucial environmental assets involved in the process include local air and water pollution, agricultural intensification, or land degradation. Crucially, greenhouse gas emissions from the regional energy and land sectors which today are marginally compared to the global yearly flows could grow substantially in the coming decades.

Together, the demographic pressure, the generally poor quality of life, and a skewed economic growth will increasingly trigger migratory dynamics, internally (and chiefly rural → (peri)urban), within the continent – from one country to the other – , and globally (mainly towards North Africa, the Mediterranean, and continental Europe). Migration is pushed by different but often interrelated drivers, including conflict, disease, seeking prosperity, political issues, a changing climate, and so forth. Crucially, economic growth *per se* can itself be a contributor to migration – as different studies have pointed out –because it can provide the sufficient income for a household to set on a journey and look for new opportunities (Falchetta and Frixa, 2019). Evidence shows that it is access to services and well-being opportunities that holds people in their countries, not income *per se* (Gabanelli and Ravizza, 2019). Thus, as witnessed over the last decade in Mediterranean countries, migration is one of the hottest issues of the political agendas of Europe, as well as a dramatic humanitarian challenge.

Altogether, the growing sources of socio-environmental and economic pressure and the inequality in access to services highlight why decisions and processes – and chiefly the infrastructure put into place and the policies enforced – taken in the present and in the near future in the region will affect the livelihoods of the African and global populations for many decades ahead.

1.2. Energy in sub-Saharan Africa

The essays presented in this dissertation puts energy at the core. Energy is a key enabler of human activities. The provision of energy services underpins the socio-economic development of nations and their growing prosperity (Fouquet, 2016): not only is energy required by all industrial activities, but it is also essential for the provision of clean water, sanitation and healthcare, as well as efficient lighting, cooling, cooking, use of mechanical power, transportation and telecommunication services (McCollum et al., 2018; Nerini et al., 2018). Thus, providing access to affordable modern energy services represents a key requirement for eradicating poverty and reducing inequalities.

This dissertation analyses a number of different and yet interrelated aspects in the context of the sub-Saharan African region putting at the core the challenges ahead for meeting the SDG 7's targets of achieving universal access to modern energy to all by 2030 and of ensuring the sustainability of the energy sector in compliance with several other SDGs and primarily SDG 13 on climate action.

To benefit the reader, here I briefly summarise the key energy-related elements and issues in the region, with a particular focus to those questions that are assessed and discussed in the next chapters.

1.2.1. Energy sector outlook and the energy access challenge

The most recent statistics on energy in sub-Saharan Africa (IEA, 2019) reveal that the region hosts more than 570 million people without access to electricity (Fig. 1.1A) and nearly 800 million people without access to clean cooking solutions. The numbers show a large prevalence of fuelwood, straw and other waste in rural areas, and a key role of charcoal in urban areas, where only over the last decade have LPG and natural gas started gaining prominence in selected countries (Fig. 1.1B). Overall, this means that modern energy is a scarce service in the region, despite the growing efforts over the last decade and the huge regional resource availability (IEA and IRENA, 2019). The predominant situation is thus one of economic scarcity (as opposed to physical scarcity).

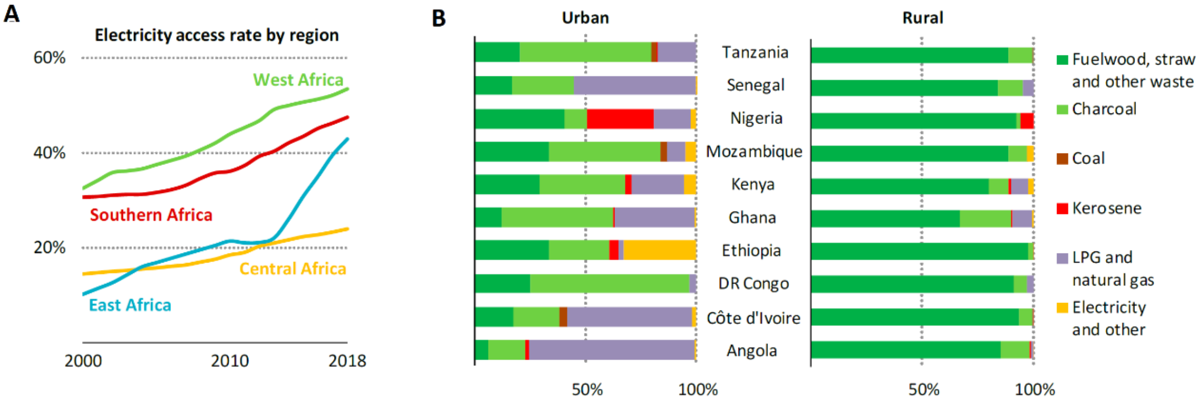

Figure 1.1: Evolution of the regional electricity access levels in sub-Saharan Africa (panel A) and share of cooking fuels in selected countries over urban and rural areas (panel B). Source: author's elaboration on IEA (2019).

Providing universal access to electricity and clean cooking would greatly enhance the living standards as well as the development prospects of the people currently lacking access. The case of electrification is illustrative of why the lack of energy access represents a major stumbling block for socio-economic development. Any developed country lists among its key priorities a secure access to electricity to foster its economic development. Electricity access to households, services, and productive activities is key to improve health conditions, increase labour and agricultural productivity, enhance overall economic competitiveness and ultimately promote economic growth and poverty reduction (refer to Chapter 3). Empirical studies have shown that expanding electricity access indeed increases time spent in income generating activities (Bernard, 2010; Bos et al., 2018; Rathi and Vermaak, 2017; Van de Walle et al., 2013), especially outside of the agricultural sector. Electrification also increases the number of manufacturing firms, their productivity and revenues (Bonan et al., 2017).

Even when considering current energy use where access is available, most countries in the region have levels of per-capita primary energy consumption of less than 20 GJ, with the main exceptions being South Africa (at about 100 GJ) and Nigeria (at almost 35 GJ). Moreover, 75% of the total primary energy demand – TPED – (which sums to about 21 EJ) in countries of sub-Saharan Africa is originated from biomass, as a result of the two thirds of the entire population collecting or purchasing, and burning daily considerable amounts of organic fuels. It must be remarked that a significant part of this thermal energy is dissipated because of the very low efficiency in use of solid biomass, also caused by the design and usage practices of traditional cookstoves. The remainder 25% is dominated by oil (about 15%) and natural gas (5%), and little residual shares for coal and hydropower (combined they reach 5% of TPED). Non-hydropower renewables (solar, wind, geothermal, and tidal energy) still account for roughly only 1% of those 21 EJ.

On the top of low current consumption levels, energy consumption has so far grown very slowly compared to the economic growth rates experienced over the last ten years in the region, with countries experiencing regular issues of lack of electric generation capacity, transmission and distribution infrastructure (for both power and liquid and gaseous fuels), reliability, and – of course – access to energy services and appliances to exploit them in the first place. Yet, over the long-run the energy system of the continent will necessarily need to expand if economic and human development are to be pursued because energy shows strong interconnections with virtually all the SDGs.

1.2.2. **Defining, tracking, and monitoring energy access**

The Sustainable Development Goal 7 sets the objective of *'ensuring access to affordable, reliable, sustainable and modern energy for all'* by year 2030 (United Nations, 2015). In particular its indicators 7.1.1 and 7.1.2 evaluate the proportion of population with access to electricity and the proportion of population with primary reliance on clean fuels and technology. But what does energy access mean in factual terms and how is it defined? The concept of energy access does not have a unique, widely-agreed, definition (IEA, 2019). Generally, it is mostly referred to as household access to minimum levels of modern energy, for both electric appliances and clean cooking needs. However, a heated debate over the quantification of those minimum levels and their measurement is ongoing (Nussbaumer et al., 2012; Pachauri, 2011; Pachauri and Rao, 2020, p. 7). The most widespread metric of access to electricity and clean cooking solutions is the share of a country's population that benefits from each energy service. However, much criticism has been raised towards this measurement approach, because it is inherently limited by a strong aggregation and mono-dimensionality, which disregards crucial questions such as reliability of supply, and the effective use beyond nominal access provision (Bhatia and Angelou, 2015). These discussions have spurred the establishment of measurement schemes, such as the *World Bank Multi-Tier Framework*, suitable for providing a multi-dimensional indicator of energy access. One of the crucial arguments emerging from these frameworks is that energy access and energy poverty are not mutually exclusive. These issues are at the core of Chapter 2. At the same time, energy access is not a static concept, but it should considered as a dynamic process following a ‘ladder’ (Bensch et al., 2017; Chattopadhyay et al., 2015; Grimm et al., 2016; Monyei et al., 2018), where different technologies and solutions gradually replace the previous ones providing greater power and supporting more appliances and uses.

Numerous initiatives have been promoted to keep track of electricity access progress. Major recent developments include the *Tracking SDG 7 report*, published yearly by a consortium of international organisations including IRENA, the IEA, and the World Bank ESMAP, and household surveys carried out by the World Bank (World Bank, 2019), which however are infrequent, scattered in a limited number of countries, and scarce of detailed information on energy use and expenditure. Recently, ESMAP has started[1] carrying out energy-access specific surveys in a number of pilot areas to provide some empirical evidence over the current status of energy access as defined and measured by the World Bank Multi-Tier Framework (WB-MTF) (Bhatia and Angelou, 2015).

The WB-MTF (Figure 1.2) is a matrix encompassing seven key dimension of energy access, namely both clean cooking and electric energy. This multi-dimensional classification is crucial step forward from the conventional definition of electricity access as a binary variable. It creates tier of quality of access to electricity defined not only on the amount of power available, but also looking at reliability, affordability, and safety indicators. A recent body of literature has shown that providing access to electricity is *per se* not a sufficient condition to ensure a sustained uptake and use of consumptive and productive appliances that can boost human and socio-economic outcomes (Burgess et al., 2020; Lee et al., 2020a, 2020b; Taneja, 2018). This evidence points at the importance of capturing the broad array of dimensions that characterise electricity access, both in research and in the policymaking.

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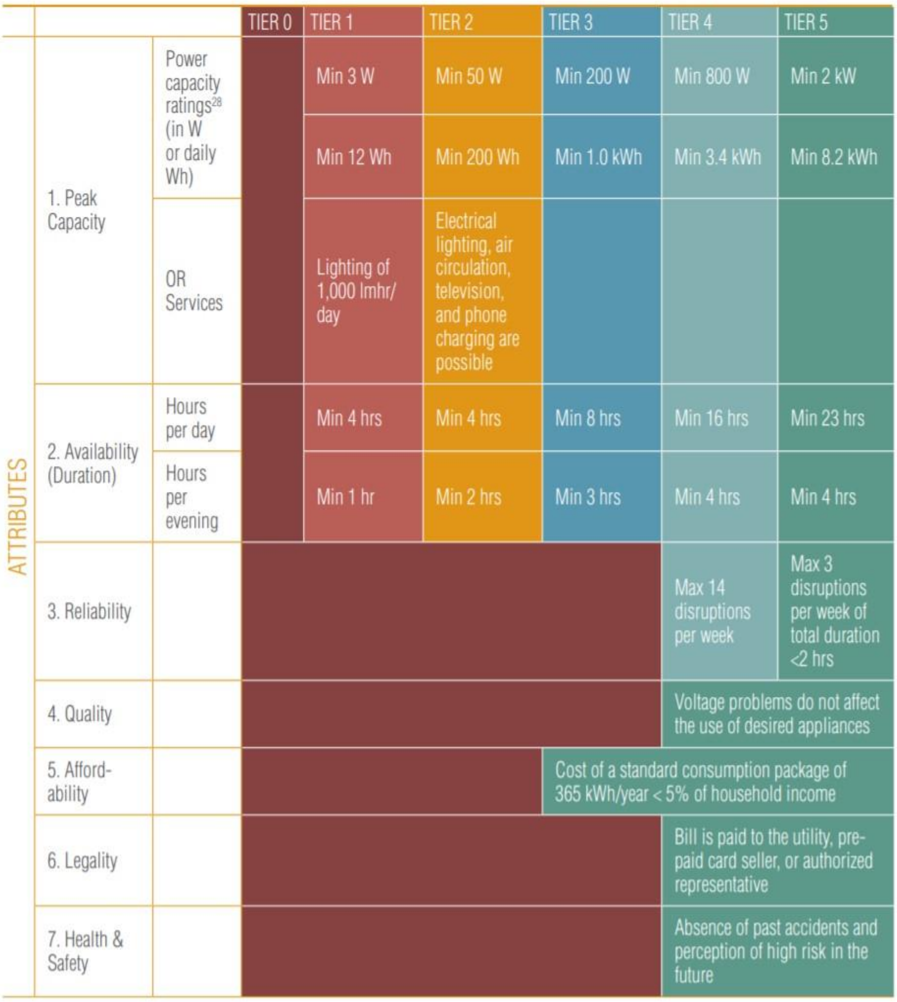
[1] For instance, as of late 2019, microdata has been released for Rwanda (https://datacatalog.worldbank.org/dataset/rwanda-multi-tier-framework-mtf-survey-2018) and Zambia (https: //microdata.worldbank.org/index.php/catalog/3527)



			TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
ATTRIBUTES	1. Peak Capacity	Power capacity ratings[28] (in W or daily Wh)		Min 3 W	Min 50 W	Min 200 W	Min 800 W	Min 2 kW
				Min 12 Wh	Min 200 Wh	Min 1.0 kWh	Min 3.4 kWh	Min 8.2 kWh
		OR Services		Lighting of 1,000 lmhr/ day	Electrical lighting, air circulation, television, and phone charging are possible			
	2. Availability (Duration)	Hours per day		Min 4 hrs	Min 4 hrs	Min 8 hrs	Min 16 hrs	Min 23 hrs
		Hours per evening		Min 1 hr	Min 2 hrs	Min 3 hrs	Min 4 hrs	Min 4 hrs
	3. Reliability						Max 14 disruptions per week	Max 3 disruptions per week of total duration <2 hrs
	4. Quality						Voltage problems do not affect the use of desired appliances	
	5. Afford-ability					Cost of a standard consumption package of 365 kWh/year < 5% of household income		
	6. Legality						Bill is paid to the utility, pre-paid card seller, or authorized representative	
	7. Health & Safety						Absence of past accidents and perception of high risk in the future	

Figure 1.2: Multi-tier Matrix for Measuring Access to Household Electricity Supply. Source: (Bhatia and Angelou, 2015)

1.2.3. Assessing and understanding energy demand

But how can a currently lacking demand be inferred, so as to plan infrastructure and policies to provide energy access? This question has long been puzzling researchers and practitioners at rural electrification agencies and energy Ministries because of the large number of local factors and assumptions that can play a role in defining communities' energy needs. While it has been show that a plausibly bi-directional link binds income and household power consumption (Hossain and Saeki, 2012), it has also been shown that the income elasticity is not linear (Poblete-Cazenave and Pachauri, 2019), but it varies at different levels of power consumption and it can also be different in different countries due to behavioural and cultural factors.

Previous studies aiming at estimate energy demand have followed a plethora of approaches, which can be clustered depending on the underlying methodology:

(i) ex-post empirical analysis (econometrics); (ii) ex-ante thermodynamic and life-cycle assessment analysis; (iii) scenario analysis. While it is beyond the scope of this introductory chapter to offer a systematic review, some of the most recent or seminal contributions screened during the time of the writing of this dissertation include the following.

Filippini and Pachauri (2004) used microdata to measure the seasonal price and income elasticities of electricity demand in the residential sector in India and derived electricity demand functions. They show that while demographic and geographical variables are significant in determining electricity demand, electricity demand is income and price inelastic. This finding supports the use of heterogeneous demand profiles dependant on the local socio-economic and geographical situation when planning energy access.

Poblete-Cazenave and Pachauri (forthcoming) measured the heterogeneity in the elasticities of households in Brazil, Ghana and India and showed that household response in electricity consumption to income changes varies greatly relative to their current income and consumption level. Using these estimates and data on the current distribution of income and power consumption, they estimate the total latent electricity demand (the hypothetical demand that would exist if access to electricity services were made available) of achieving universal access to electricity services. This result underpins the importance of not assuming a linear relationship between income and power demand. A similar result is found by Fabini et al. (2014), who develop a predictive model for mapping induced (i.e. latent) residential demand for electricity and apply it on Kenya using high-resolution geospatial data.

Adeoye and Spataru (2019) build an hourly model of electricity demand for 14 West African countries. They characterise demand heterogeneously and use an appliance-based approach and validate their model with real data. The methodology allows simulating seasonal variability in the demand and forecasting the 2030 demand, including newly electrified households. The authors underline the importance of carefully considering household appliance ownership and usage patterns.

Kotikot et al. (2018) present a geospatial framework for estimating household electricity demand that could inform infrastructure-planning tools. They use a gridded population dataset together with survey data on appliance ownership This enables them to estimate the current generation capacity deficit in South Africa, Nigeria, Kenya, and Uganda, their case study countries.

In a seminal contribution, Louw et al. (2008) studied the determinants of electricity demand for newly electrified low-income African households. Based on field data, they find that income, cooking fuel usage, appliance ownership and credit obtained are significant in determining consumption levels within households.

Finally, it is worth including in this review the recently introduced concept of *decent living energy* (by Rao, Min, and Mastrucci, 2019), an approach which enables synthetizing energy needs starting from the energy embedded in the materials and services that people need to satisfy a set of basic human needs. This approach draws from life-cycle assessment methodology (i.e. it considers the entire supply chain) and is particularly useful to understand the true energy requirements of countries to tackle energy poverty, beyond indicators that are limited to the final use of energy. In this thesis, and in particular in Chapter 3, I refer to a similar bottom-up, service and appliance-oriented approach, to estimate energy requirements to provide access to electricity to those without access.

1.2.4. **Planning energy supply**

Once a certain demand has been calculated on the basis of either bottom-up assessments or top-down political objectives, it is necessary to assess the optimal infrastructure to satisfy those targets. Broadly speaking, the literature is here divided into the economic literature performing ex-post modelling of data on energy carrier choice, and the energy engineering literature building cost-minimisation planning models. In the latter research strand, traditional energy models, such as TIMES (Loulou and Labriet, 2008), or integrated assessment models, e.g MESSAGEix (Huppmann et al., 2019) or WITCH (Bosetti et al., 2007), are designed to satisfy an aggregate demand based on an existing grid infrastructure. Conversely, energy access planning requires a detailed account of the basket of different solutions that exist to provide access to electricity, namely both centralised and decentralised solutions. The latter include, for instance, mini-grids and standalone photovoltaic modules. Recent evidence (IEA, 2019) has shown that these could account for nearly one third of new electrification in sub-Saharan Africa until 2030. Moreover, a correct representation of the cost of expanding both the transmission and distribution gird is of crucial importance in determining the optimal electrification mix.

To fit these needs, a number of bottom-up cost assessment and comparison tools have been developed. These include OnSSET (Korkovelos et al., 2019; Mentis et al., 2017) and the related online Global Electrification Platform, the Reference Electrification Model (REM) (Ellman, 2015), Network Planner (Kemausuor et al., 2014), the EC-JRC model (Moner-Girona et al., 2019; Szabo et al., 2011), the Energy Access module of the IMAGE integrated assessment model (Dagnachew et al., 2017; van Ruijven et al., 2012). These tools calculate and compare the levelised costs of electricity (LCOEs), defined as

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + O\&M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

(Eq. 1.1)

where, for each technology, I_t represents the investment cost in year t, $O\&M_t$ are operation and maintenance costs, F_t are fuel costs, E_t is the electricity generated, r is the discount rate, and n is the lifetime of the technology in question. In particular, the cost of each technology is defined based on an array of parameters which include both local potential (for RE) and infrastructure and terrain barriers (e.g. distance to the existing and planned grid, elevation, slope, land cover).

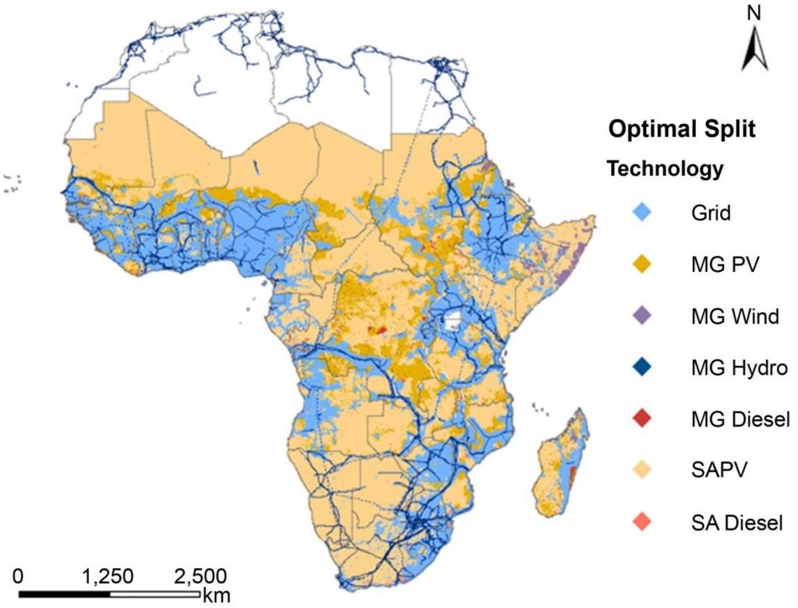


Figure 1.3: Example of the result of a least-cost spatially-explicit electricity access assessment tool. Source: Mentis et al. (2017).

These modelling instruments are thus able to generate high-resolution spatially-explicit maps of energy least-cost energy supply technologies to meet certain demand objectives (see an example in Fig. 1.3.) Of course, their results are highly sensitive to a number of parameters (see Morrissey 2019), and to the demand formulation (Leea et al., 2019). An application of these bottom-up supply-side electricity assessment tools is offered in both Chapters 4 and 5.

1.2.5. The role of governance, regulation, and investment in the energy sector

The energy sector presents both challenges which are common to all heavy infrastructure sectors, and issues which are unique in their nature. In countries with electricity access gaps, it is often the case that the power generating capacity is limited. As a result, a share of the national demand remains unmet and electric distribution utilities are forced to adopt load shedding policies. Moreover, a large number of power plants in developing countries face maintenance and fuel provisioning security issues. Thus, on the one hand electricity access planners face supply-side constraints that make it challenging to broaden the consumer base (and thus the domestic demand) without ramping up the sources of supply. On the other hand, recurrent supply reliability issues are faced by grid-connected consumers (e.g. the World Bank reports that in sub-Saharan Africa firms have faced an average of 9 outages per month in 2018), who thus are not benefitting from a secure access to energy.

Concurrently, the national transmission and distribution network likely have a limited extent and coverage. Generally, the existing infrastructure connects power plants to the main urban areas, while the bulk of rural settlements (where most of the population lives) remain far-off from the network. The infrastructure supply inequality determines a situation of strongly unbalanced electricity access levels in urban and rural areas (International Energy Agency et al., 2019). This suggests that commonly reported national electrification levels are hiding wide disparities, especially considering that the bulk of the population of developing countries lives in rural areas (World Bank, 2018). Moreover, as a result of the rapid ongoing urbanisation trends, significant hotspots of people without access are emerging in the peri-urban areas surrounding cities, where either the local distribution network is lacking despite the geographical proximity to existing electric substations, or consumers simply cannot afford to pay for grid connection charges.

The main economic roots behind the insufficient or poorly maintained generation capacity and the limited extent of grid networks include:

1. The considerable upfront investment requirements and operation costs of power generation facilities. According to Enerdata (2016) the costs of new power plants in Africa range between 2,000/kW for hydropower, 1,112 and 1,290 USD/kW for open and combined-cycle gas-fired turbines, respectively, 2,153 USD / kW for coal-fired plants, 2,011 USD / kW for utility-scale solar PV plants, 11,300 USD / kW for solar concentrated power plants, and 2,450 USD / kW for wind power plants below 100 MW in size. A steeply growing demand for power as a result of both economic development (e.g. 2.4% and 6.8% average in Africa

and South Asia in 2018) and population growth (2.7% and 1.2% average in Africa and South Asia in 2018) implies large capacity addition requirements, which in turn necessitate substantial investment, which in the past decades have not been adequately channelled due to the reasons discussed in the next sections of this section.

2. The crucial role of running cost. The lack of maintenance and aging of power plants has led to a situation where 25% of the install capacity in the continent is unavailable (Findt et al., 2014). The supply security of the fuels necessary to power existing plants is another issue. For instance, the installed capacity in Nigeria (above 10 GW, USAID 2019) is theoretically adequate to satisfy the current national demand, and yet disruptions in the supply due to damages in the pipelines, geopolitical issues, or price volatility has led to their under-exploitation and thus to issues in guaranteeing a secure supply of electricity to grid-connected consumers (e.g. see Occhiali & Falchetta, 2018). Hydropower plants – which in many countries which electricity access gaps are the main source of power supply – are also constrained by increasingly frequent and prolonged drought periods which force utilities to suspend generation or limit the operational capacity (Falchetta et al., 2019). Countries heavily relying on coal – such as South Africa, India, and China – are facing substantial socio-economic pressures. For instance, South Africa is water-scarce and faces recurrent droughts which require the Government to curtail residential water use. This is also due to the very large cooling water requirements of coal-fired plants. In Asia, burning coal is perceived as increasingly costly for the social impact it has been exerting on public health.

3. The high expansion costs of the grid, ranging from 3,000 USD per km of low-voltage distribution line to 30,000 USD per km of high-voltage transmission line, which in turn imply an average of 1,500 USD for each new household connected to the national grid (Rosnes and Vennemo, 2009). These costs are even more difficult to bear considering that the central planner is facing high discount rates (medium-term government bonds average a 15% yield in sub-Saharan Africa), and thus the cost of capital is high. This, of course, discourages long-term infrastructure investment.

4. The degree of dispersion of the population – particularly in rural areas – which results in low population densities (for instance, the average for sub-Saharan Africa is 51 inhabitants/km^2 against 455 inhabitants/km^2 in India, where most connections have indeed been achieved through direct

connection to the national grid), and thus render the investment often not economically profitable.

5. The low ability-to-pay and little short-run consumption of new customers (Blimpo and Cosgrove-Davies, 2019; Jacome et al., 2019; Taneja, 2018), which together do not allow the national utility to recoup the large upfront investment borne to connect new households to the national grid.

At the same time, the budgetary deficit of national utilities, investment unattractiveness for private capital, and the low ability-to-pay of households and the role of connection charges all constitute further barriers to the expansion of energy systems in sub-Saharan Africa.

Firstly*,* traditionally, electricity systems are developed through investments made by national utilities, which allow the achievement of strong balance sheets through the sale of electricity produced at large-scale power plants. Earnings serve as the primary financing source for grid infrastructure expansion and strengthening, new capacity additions, and, in many markets, they allow utilities purchasing power from independent power producers (IPPs). In developing countries, most of the national transmission and distribution utilities are instead running on quasi-fiscal deficit. Figure 2 illustrates a comparison of electricity supply costs (capital and operational) with cash collected by the national electric utilities of sub-Saharan Africa. It reveals that the bulk of the utilities require yearly financial support from the Government and thus steadily contribute to the increase of national debts.

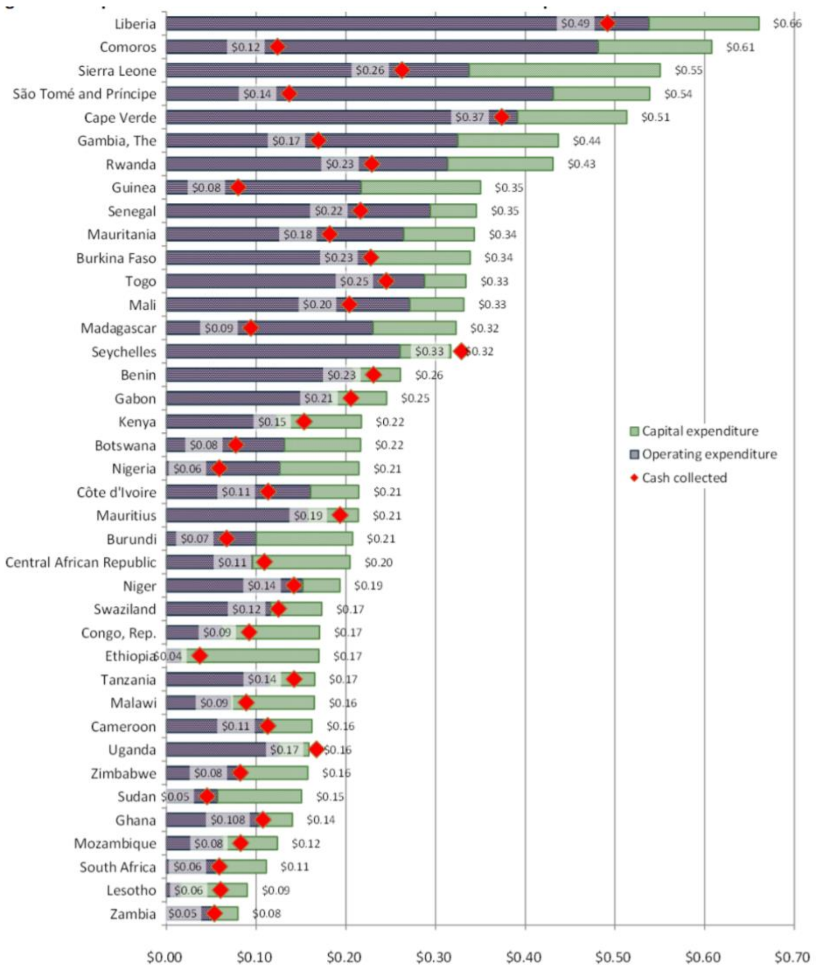


Figure 1.4: National utilities of sub-Saharan Africa: comparison of electric supply costs with cash collected in 2014 ($/kWh billed). Source: Trimble et al. (2016).

The key reasons behind the deficit include the significant transmission, distribution and bill collection losses, overstaffing and, most crucially, poorly designed customer subsidisation, which leads to excessively low electricity prices. Universal energy subsidies – which for decades have prevailed in developing countries – are inequitable, as they mostly benefit higher-income groups that consume the most (Vagliasindi, 2012). This type of subsidies is also regressive, because access to the electricity grid through the national grid is highly skewed toward higher-income groups. Second, universal electric energy subsidies are profoundly detrimental for the development of energy systems. In fact, they create a disincentive for maintenance and investment in the energy sector, perpetuating energy shortages and low levels of access. Subsidies are only efficiently design if they target at reducing connection charges and stimulating new connection to the national grid, rather than reducing marginal prices of electricity for customers. Together, budgetary deficit-related factors represent an important concurrent cause to the limited expansion of the national grid, and thus the lack of electricity access. Secondly, historically, the fundamental cause for the lack of power supply infrastructure – i.e. of the limited installed capacity and extent of the transmission and distribution grid – has been the paucity of private investment (an issue at the core of Chapter 5) in the power sector of developing countries. Because of macroeconomic, political, and monetary instability, the cost of lending local capital is extremely high, with medium-run government bonds often yielding more than 15%, compared to – for instance 1.8% is the US or even -0.527% in Germany as of 2019. Independent-power-producers (IPPs) are crucial players in the development of the power sector of developing countries, because they complement and – on the road towards a competitive power supply market – gradually substitute the role of the national utilities. This is because of the lumpy nature of electrification investment, which requires significant amounts of capital upfront, – which in turn the public funds of a developing countries cannot afford due to the large number of additional priorities to be met under tight budget constraints. A broad stream of literature has indeed highlighted that countries with policies, institutions, and general investment environment attracting IPPs are those which have exhibited the steepest improvement in electricity access levels (Eberhard et al., 2018, 2017a; Eberhard and Gratwick, 2011). Kenya and South Africa are the two most prominent examples for the last decade.

On the other hand, countries classified as insecure by investors and lacking a regulatory framework for private power and infrastructure suppliers (a good reference is provided by the Regulatory Indicators for Sustainable Energy database, RISE (2017)) have historically struggled to expand access and domestic supply capacity. More recently, international donors, financial banks and, pivotally, state-owned enterprises from China, have supplied significant investment even towards these countries, albeit to a lesser extent than in countries with a more suitable regulatory framework. As seen in Figure 4, the role of China is particularly crucial. Over the last decade, the country has become the first source of investment in power-generating infrastructure in sub-Saharan Africa (Eberhard et al., 2017b). According to the International Energy Agency (2016), Chinese companies (90% of which state-owned) were responsible for 30% of new power capacity additions in SSA between 2010 and 2015—with a total investment of around 13 bn. USD over the quinquennium. Chinese contractors have built or are contracted to build 17 GW of power generation capacity in SSA from 2010 to 2020, equivalent to 10% of existing installed capacity. These projects have hitherto targeted at least 37 countries out of 54 in the region.

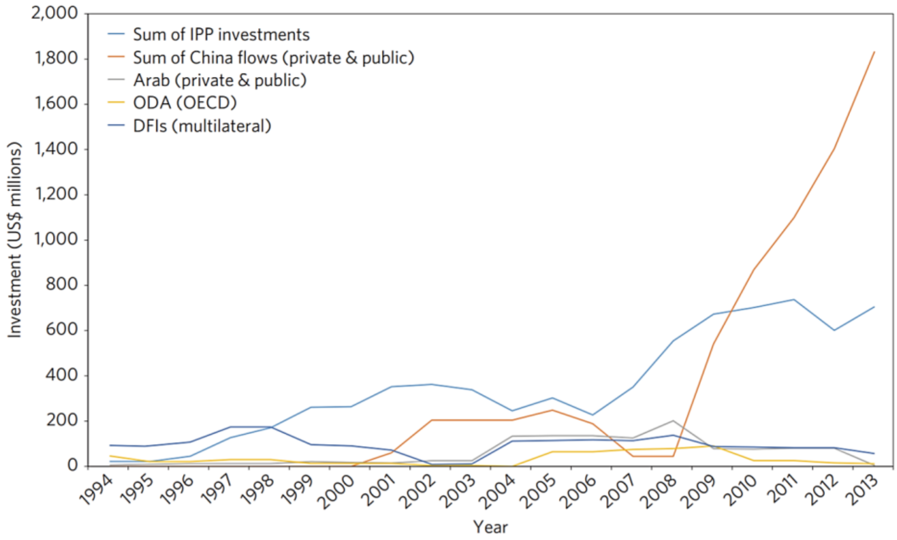


Figure 1.5: Investment flows in power generation infrastructure in sub-Saharan Africa. Source: Eberhard, Gratwick, Morella, & Antmann (2016)

Finally, roadblocks to electricity access do not only stem from the supply-side, but they also relate to the inability to pay of income-constrained households. The issue involves several dimensions, all of which can be tackled by an appropriate policy design.

1. The first is determined by the charges levied by national utilities for new connections to the central national grid, which traditionally have been levied in a lump sum of an amount higher than the monthly income of most households.

2. The second aspect concerns the running costs, i.e. the price of electricity, and the capacity of the national utility to enforce its regular collection.

3. A third aspect is related to the reliability of the electricity provision from the national grid. An unreliable supply with frequent outages may induce households and, particularly, small business enterprises, hospitals and schools to purchase a back-up generator, which determines a double cost borne by the consumer for benefitting from the electricity service, or even the decision not to connect to the grid.

1.2.6. **Renewables and sustainability of the energy system**

In the context of the Paris Agreements and the global efforts to keep global warming “well below 2° C”, currently sub-Saharan Africa plays no major role.

The energy-related greenhouse gas emissions of the continent stood at about 1.1 Gt CO_2 in 2014 (World Resources Institute, 2017), which is roughly one ninth of China's, irrespective of the two regions having a similar population. Of this 1.1 Gt, one third stems from electricity and heat generation, one additional fourth stems from the combustion of other fuels (i.e. chiefly cooking-related biomass combustion), and one further third alone is the result of fugitive emissions, such as gas flaring. Nevertheless, the long-run pathways of energy demand and of the carbon intensity of the economy might – over the medium and long-run – become very significant for global emission pathways.

In this dissertation, substantial focus is put on analysing how to enable a universal, sufficient, and reliable access to electricity in the region. In this context, wide analysis and discussion space is devoted to the role of renewable sources of electricity generation, and in particular in the context of mini-grids and standalone access solutions. At the same time, the dissertation includes a specific analysis (Chapter 6) on the impact that climate change will exert on hydroelectricity – both structurally and through extreme hydroclimatic events. Hydropower is a key technology to guarantee a clean development of SSA power sector, both as a baseload power generation technology, and as a balancing and storage instrument through reservoir management (Hunt et al., 2020), pumped-storage, and synchronisation with variable renewable sources of electricity (Sterl et al., 2018). It already plays a pivotal role in the region, with 40% of total installed capacity, and its role is expected to gain prominence as a result of the construction of new, large-scale power generating dam exploiting the big techno-economic hydropower potential found in the region (Gernaat et al., 2017), and more than 95 GW installed by 2040 from the current 27 GW.

Yet, it must be remarked that a comprehensive analysis of the energy system of sub-Saharan Africa across its demand sectors is outside of the scope of this dissertation. Relevant examples of recent work in this direction include (Taliotis et al., 2016), who modelled possible future paths for Africa's energy future and the related emissions finding that under the current energy policies and found that the universal access to modern energy will not be met by 2030 and thus policies to accelerate the changes in energy structure are required for sustainable development.

1.3. The feedback nexus between energy supply, economic development, and energy demand growth

A broad stream of literature has investigated the socio-economic interactions following the provision of electricity to households and communities that previously lived without it.

Previous studies have shown that increasing affluence leads to growing electricity demand “at the extensive margin” after electricity infrastructure is provided, i.e. as low-income households buy and use durable appliances (Wolfram et al. 2012). Similar conclusions were reached by Louw et al. (2008), who assess the determinants of electricity demand for newly electrified low-income African households, finding that along with asset ownership and market access, income is an important predictor of consumption level. At the same time, per-capita energy consumption is itself found to be statistically associated with economic growth, although the magnitude and direction of causality between the two is uncertain and context dependent (Belke et al., 2011; Wolde-Rufael, 2009).

However, the real challenge is to isolate and measure impacts at the local level. In fact, empirical research in Development Economics has been pursuing a variety of causal inference techniques to investigate the potential structural transformation, such as labour market and job creation, brought by the provision of electricity. In turn, structural transformation and economic development could initiate a feedback loop on electricity demand. Yet, the evidence over the welfare gains of electrification and the rollout of structural dynamics remains mixed and very dependent on the geographical, social, cultural and economic context in question (Jimenez, 2017) and producing sound causal inference studies in the context of rural electrification remains challenging (Bernard, 2012).

Among the recent or seminal literature, Riva et al. (2018) systematically review literature analysing the impact and feedback loop of electricity provision on rural development. They introduce causal loop diagrams of the underlying dynamic and endogenous complexities. Based on the reviewed studies, the author conclude that electricity provision is a necessary but not sufficient condition to unleash positive electricity-development dynamics, as complementary activities and infrastructural preconditions are required.

In a seminal contribution, Barnes and Binswanger (1986) analyse the impact of rural electrification and infrastructure on agricultural changes between 1966-1980 in India. They find a significant impact on the uptake and use of electric water pumps for irrigation, but they measure a only limited boost in agricultural productivity.

Fried and Lagakos (2021) provide evidence from a panel of rural Ethiopian villages during its recent expansion of electricity supply. They find that electrification raised irrigation rates, agricultural yields and non-agricultural business activity. Moreover, they highlight that electrified villages showed higher net positive migration flows.

Chhay and Yamazaki (2021) carry out a causal inference study in Cambodia based on nationally represented survey data between 1998 and 2008. They find that the provision of electricity triggered a labour shift away from agriculture, dominated by an increase in non-agricultural self-employment activities.

Bensch et al. (2011) carried out an evaluation of electrification in Rwanda, finding mixed evidence over income or educational gains. Conversely, Dinkelman (2011) found a strong and positive short-run impact on electrification of female employment. The paper was however recently criticized for potential methodological pitfalls in Bensch et al. (2020). Tagliapietra et al. (2020) carried out an electrification impact assessment study in the context of Nigeria looking at labour market outcomes. They show a shift out of agricultural employment into non-agricultural employment with some evidence of a positive effect on overall labour participation. Akpan et al. (2013) examine the impact of rural grid-based electrification on rural micro-enterprises in Nigeria, finding they tend to be more profitable, although with mixed statistical significance. Relatedly, an analysis by Vernet et al. (2019) in Kenya shows that rural electrification increases the rate of micro-enterprise creation, along with community income and expenditure, with a disproportionate positive impact on women.

In the context of this complex literature background on the electricity provision-economic development bidirectional nexus, it must be remarked that the Essays contained in this dissertation, and in particular Essay 2 (M-LED: multi-sectoral latent electricity demand assessment for energy access planning), are not explicitly modelling structural change dynamics. Nonetheless, these dimensions are in part accounted for implicitly: while the M-LED platform seeks to fulfil certain *a-priori* defined energy service needs, such as the uptake and use of given appliances in households, hospitals and schools, the estimated load profiles for agricultural uses (irrigation and crop processing) and small commercial and other productive uses (expressed as a mark-up on top of the residential demand) are implicitly assuming the resulting energy demand from certain structural changes, such as the mechanisation of agriculture and the uptake of productive activities by households.

1.4. The Nexus between climate, land, energy, water, and food

Already from the subtitle, this dissertation makes explicit reference to the concept of the *Nexus*. The *Nexus* is a concept that was first introduced by Hoff (2011), which describes it as *“an approach that integrates management and governance across sectors and scales”.* More specifically, in this dissertation it refers to the analysis of sectoral interdependencies and impacts and the pursuit of integrated assessments that are able to capture multiple challenges at the same time or the spillovers of actions in one sphere into the other spheres. In particular, given the scope of this work, I will narrow this approach to the climate, land, energy, water, and food sectors, which have been the key focus of a broad stream of literature (Johnson et al., 2019).

Since the concept of nexus is very broad, in the context of this thesis it can be thought of as a tendency to think about the core energy-related challenges analysed with a broader view encompassing the interaction that energy shows with climate, land, water, and food and – ultimately – economic development. For instance, Chapter 3 addresses the challenge of understanding the energy requirements to provide electricity access to multiple sectors, including agriculture. This includes irrigation water needs and the related pumping energy, as well as the energy required for crop processing facilities. Chapter 4 evaluates the role of (mostly exogenous) anthropogenic climate change for energy demand for air circulation and cooling services in a way that electricity access planning is synergetic with climate adaptation. Chapter 6 analyses the impact chain that goes from climate, through water, to energy in a large number of countries in sub-Saharan Africa where hydroelectricity is the primary source of power generation, with dams also constituting crucial pieces of infrastructure for irrigation purposes and creating geopolitical issues in the context of transboundary river basins. On the other hand, Chapter 7 analyses the impact chain that stems from economic growth and goes through behaviour and food-related choices to eventually exert an impact on both the local and global environment. This includes land, water, and energy consumption, and the emission of greenhouse gases responsible for anthropogenic climate change.

It is thus clear that all the aspects analysed in this work, including the energy access challenge are deeply interrelated. While unavoidably constrained by a limited scope, this dissertation will thus pay particular attention in discussing the inter-sectoral interdependencies of every core issue from a *nexus* perspective.

1.5. Beyond aggregates: geospatial analysis and bottom-up modelling

This ambitious workplan proposed in this thesis requires a rigorous methodology that can deal with the complex nature of the problem. In particular, the core methodological principle followed by this dissertation is to always go beyond aggregates, as long as the data is allowing for it. The underlying reason is that so far development indicators – in particular in the context of developing countries – have mostly been provided at national scales. Yet, often policies and conditionality agreements are based on such indicators, which however rely overwhelmingly on simple averages and aggregates that mask underlying variations and distributions. National-scale analysis and regional modelling are likely to average out uneven patterns of changes and impacts across regions and groups within the same nation. The overall conclusion of this work is that – for instance – if benchmark is only based on national aggregates, there is no guarantee that everyone will benefit from the achievement of the Sustainable Development Goals.

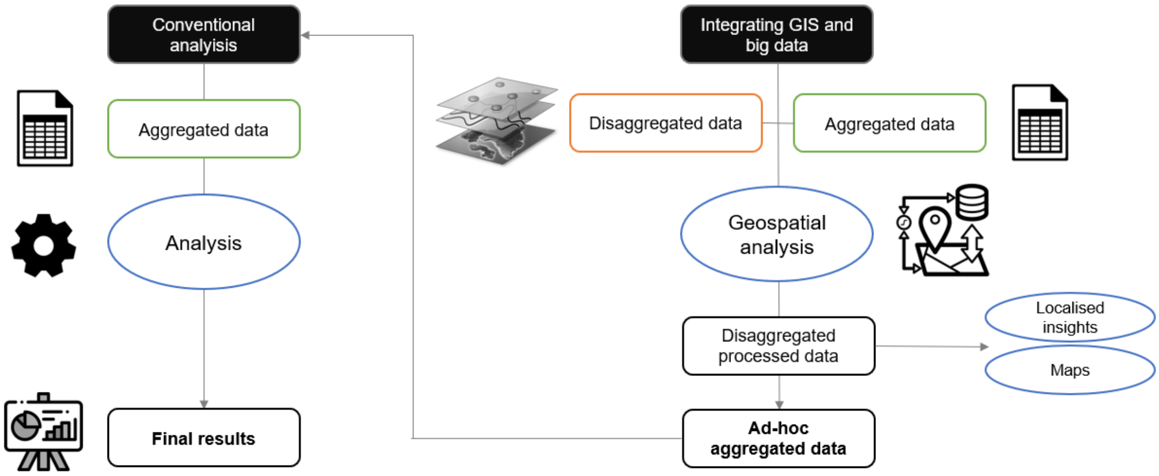


Figure 1.6.: Archetypical spatial data processing and integration pipeline as recurrently adopted in this dissertation. Source: Author's elaboration.

To tackle this pitfall, the essays presented in this dissertation share a mutual characteristic in their diversity: they perform sub-national analysis of spatially-explicit data. Figure 1.6 highlights the archetypical spatial data processing and integration pipeline that is recurrently adopted in the essays part of this dissertation. A significant portion of the time spent working on this dissertation was employed to retrieve, process, and analyse georeferenced data useful to address the research questions. These data include satellite, survey, and model-based information on demographic, social, economic, environmental, and infrastructure aspects. As the essays part of this work will show, combining this information allows drawing insights that are simple invisible when looking at non-spatial data, and that often shed light on neglected or disregarded aspects, which can yet have a dramatic impact on public and private decision-making and the international view of crucial development challenges.

In most instances, open-source GIS software and algorithms have been employed to process the data and carry out the analysis. A non-exclusive list includes QGIS, GRASS-GIS, SAGA-GIS; R packages *raster* and *sf*; and the

Google Earth Engine platform. A great acknowledgment from my side must go to the developers of these instruments, without which no portion of the work presented here could have been possible.

1.6. Scope of the thesis

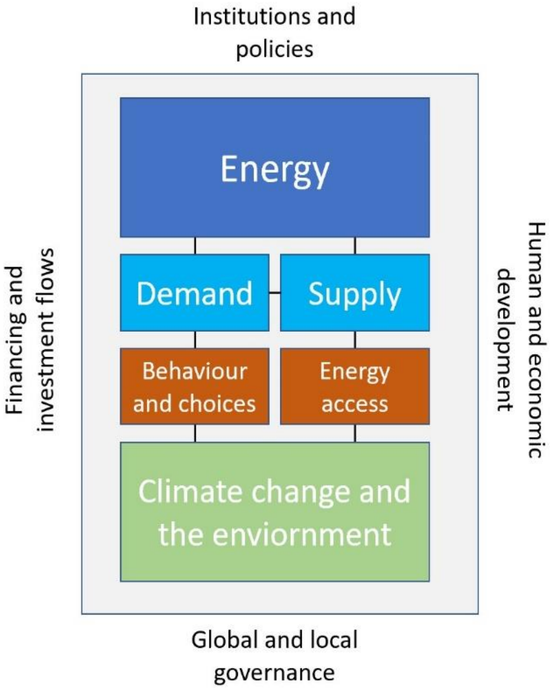


Figure 1.7: Scope of the thesis.

Overall, the work collected in this Dissertation is an attempt at a better understanding of some key crucial aspects that are an integral part of the four pillars in the framework depicted in Figure 1.7: (i) the existing infrastructure, its planning, and its role for enabling development, (ii) the institutions and policies that underpin the energy-related choices, (iii) the flows of investment and the financing institutions that enable structural transformations of the system, and (iv) the deep links between energy, the environment, climate change, and the economy, which together drive human development across its variety of dimensions, which are encapsulated in the United Nations Sustainable Development Goals (SDGs) (United Nations 2015).

The starting point assumed here is that energy systems analysis encompasses the two principal dimensions of demand and supply (Galarraga et al., 2011). In particular, in the case of energy in developing countries as it is the case in sub-

Saharan Africa, energy supply is tightly linked to energy access (IEA, 2019), i.e. the availability of energy infrastructure and services to the population. The effective (or met) demand is conditional to the availability of energy supply (Bhatia and Angelou, 2015), but it is mediated by human and social choices (Wang and Li, 2016) and behaviour (Stephenson et al., 2010). Finally, a bidirectional relationship links energy to the sustainability dimensions of climate change (with energy being both a driver (Rogelj et al., 2015) and a system undergoing feedback impacts (van Ruijven et al., 2019) and the broader environment, encompassing land (Roe et al., 2019) and water (Van Vliet et al., 2016) resources.

In this context, the final objective of this dissertation is to quantitatively assess some crucial aspects at the interplay of sub-Saharan Africa's development and its global impacts. The first aspect is access to modern energy, and in particular to electricity. In 2020, more than 500 million people are still without access to electricity in SSA. This means that they have no access to the most essential residential services, while they are deprived of the opportunity to seek income growth. The second is the reliability of the energy system and the role that climate change can exert on both the demand and the supply sides. The third bears greater complexity, because it encompasses the intersectoral nexus interdependencies between ensuring universal access to electricity and socio-economic development. Each essay of the dissertation exploits a set of methodologies and analytical tools to examine and provide insight into aspects that African policymakers should consider putting at the heart of their agendas because they will exert a strong impact on the prosperity and livelihoods of their peoples.

Overall, the thesis inserts itself in different research fields, which cannot be restricted to Energy Economics or Integrated Assessment, but encompass different aspects linking the energy, environmental, and human dimensions of energy in sub-Saharan Africa. A non-exclusive list of the research questions addressed by this dissertation is the following:

- How is the energy access situation changing in sub-Saharan Africa?
- What is the role of a bottom-up, multi-sectoral assessment in planning energy access compared to more aggregated assessments?
- What role will governance and regulatory quality in the energy sector of countries of sub-Saharan Africa in attracting private investment and defining the technologies that can most efficiently provide access to everyone?
- What implications does the need to adapt to future heat stress have for energy demand and electricity access planning?
- How could climate change render the African power sector more vulnerable, in particular given its large reliance on hydropower?

1.7. Structure of the thesis

The remainder of this work is structured as follows:

The first essay introduces the reader to the matter of electricity access. This illustrates the role of satellite data in providing an improved understanding of the electricity access situation with respect to the existing statistics provided by international organisations and national governments. It presents the methodological approach, including the validation of the estimates and the comparison with other global sources, as well as the main results in terms of inequality in the current electricity access and use levels in the sub-Saharan African region.

The second essay builds on this analysis by developing a complex energy modelling framework to estimate the community energy needs where access is currently lacking, in particular in rural areas. This assessment is not restricted to residential use of electricity, but it includes a detailed, device-based account of power needs for agricultural irrigation, crops processing, small and medium enterprises, schools, and healthcare facilities. The estimated demand profiles are used to simulate a number of scenarios of electricity access planning in Kenya to show the importance of considering multiple demand sources beyond residential in order to provide an electrification strategy which truly overcomes energy poverty.

The third essay analyses a specific aspect at the interplay between electricity access planning, household energy demand and climate change: indoor air cooling. In fact, the lack of power at home prevents households from autonomous adaptation to ensure thermal comfort. In this essay, I combine climate, demographic and satellite information to produce a spatially-explicit estimate of the distribution of the global unmet air cooling demand for ensuring thermal comfort among communities lacking access to electricity, I evaluate the power requirements for currently unelectrified households to guarantee residential thermal comfort and the country-specific feedback CO2 emissions. Finally, I evaluate the impact of the estimated cooling energy needs on the system configuration and investment requirements for an effective, adaptation-capable electricity access planning among energy poor households.

The fourth essay brings the technical analysis closer to the governance and regulatory dimensions. It introduces an Electricity Access Governance Index based on multiple indicators and implements it into the IMAGE spatial electrification model through its modifier effect on national discount rates. The purpose is showing that the quality of policy is crucial in attracting private and international investors, and that a poor regulatory framework will not only render electrification objectives more costly, but also affect the optimal technological mix.

The fifth and final essay focuses on a related but distinguished issue: the fact that a large number of countries in sub-Saharan Africa currently rely very largely on hydroelectricity for their domestic supply, and some large projects might exacerbate the dependency. In turn, this renders the power sectors of these countries very exposed to the impact of hydroclimatic extremes. A systematic review of the situation, of previous modelling work on the topic, and a comprehensive analysis of relevant data is offered to draw conclusions on how to implement a more resilient power sector.

A conclusive discussion section concludes the dissertation by linking the main findings from each essay and putting them into perspective, with specific reference to the methodological novelties introduced in the dissertation and the key implications for decision-makers at different levels.

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2. Tracking of progress towards universal access to electricity and the related inequalities with satellite data in sub-Saharan Africa

2.1. Introduction

In 2019, the International Energy Agency (IEA) reported that the global population without access to electricity had dipped below 1 billion for the first time (IEA, 2018). Yet, the numbers released in the *Tracking SDG 7 Energy Progress Report 2019* (IEA et al., 2020) and additional global assessments (Aklin et al., 2018; Marwah, 2017) highlight that this progress has been uneven both across and within different macro-regions of the world. The bulk of the improvements have been observed in Central and Southern Asia and few areas of Africa. In fact, nearly two thirds of those still without access to electricity – about 570 million people – are located in sub-Saharan Africa. The continent is home to 30 countries with electrification levels below 50% (IEA et al., 2020). At the same time, while recent evidence shows that falling costs might soon make electricity an attractive alternative for satisfying cooking needs (Batchelor et al., 2018; Dagnachew et al., 2019), most cooking activity in the region still relies on solid-biomass (IEA et al., 2020) (with the notable exception of South Africa, where electricity has gained a prominent role, Dinkelman, 2011), contrary to what is targeted by SDG7's indicator 7.1.2.

While these statistics provide a clear picture of global trends, fundamental uncertainties remain. Firstly, electricity access is still measured in a mostly binary fashion, as the share of a country's population that has access to an electric energy supply source. Binary indicators are inherently limited by a strong aggregation and mono-dimensionality and disregard crucial questions such as reliability of supply, and the effective use beyond nominal access provision (Nussbaumer et al., 2012; Pachauri, 2011). Such dissatisfaction has spurred the development of new measurement frameworks – a leading one being the World Bank Multi-Tier Framework (Bhatia and Angelou, 2015) –, but little data based on these approaches has emerged (survey results for Zambia, Ethiopia and Rwanda have been published online (World Bank, 2019a) as of early 2020). Moreover, according to SDG7's energy abundancy and mobility requirements (Monyei et al., 2018), only populations with access through the national grid or mini-grid solutions are compliant with sufficient energy access standards, while standalone decentralised solutions (IEA, 2019) such as solar kits, can be inadequate (although the surge in their installation Bensch et al., 2018; Grimm and Peters, 2016) and their role as a first step up the energy ladder (Grimm et al., 2017; Lay et al., 2013 must be acknowledged). Secondly, the most common electricity access statistics are expressed at the national scale and thus fail to reflect sub-national heterogeneity. More spatially-detailed information is, however, essential for clearly determining the electrification status of a country and tracking its progress towards the Sustainable Development Goals. Thirdly, electricity access measurement relies predominantly on expensive and unwieldy household surveys that are labour-intensive and rapidly outdated. Finally, it has been shown (Numbers, 2013) that in African countries official statistics and statements and numbers on progress towards universal and reliable energy supply (Trotter and Maconachie, 2018) – can be affected by statistical growth. This is defined (Jerven, 2013) as growth of development indicators occurring by assumption in the lack of reliable information, or with the deliberate objective of attracting more foreign investment. Yet, information provided by Governments and Ministries is the same that becomes readily accessible from international databases.

Satellite data have been employed in earlier studies (Andrade-Pacheco et al., 2019; Doll and Pachauri, 2010; Dugoua et al., 2018; Min et al., 2013) to quantify electricity access levels by assessing the presence of radiance with a wavelength compatible with that of electric light during nighttime hours (Falchetta et al., 2019; Levin et al., 2020). Previous seminal applications have shown that combining nighttime lights and human settlement datasets can proxy electricity access levels and track the rollout of electrification even at a local scale (Burlig and Preonas, 2016; Min and Gaba, 2014). These data have also been used to model changes in electricity consumption within provinces (in countries where disaggregated data is available for validation purposes) (Hu and Huang, 2019; Jasiński, 2019), detect power supply disruptions (Falchetta et al., 2020) and outages (Román et al., 2019; Wang et al., 2018), map the power transmission and distribution infrastructure (Arderne et al., 2020), and measure economic development and inequality sub-nationally (Michalopoulos and Papaioannou, 2014). Yet, the main limitations of the literature exploiting nighttime lights to keep track of electricity access in developing countries include the fact that light has been considered mostly in a binary fashion, without exploring the effective level of radiance detected and exploiting it to derive and validate proxy measures of electricity access quality for electrified households in data-scarce regions.

Moreover, little is known of how well satellite nighttime lights imagery can be used to assess access through different technological solutions – which is crucial due to the surge of mini-grids (Peters et al., 2019) – and predict inequalities in electricity access progress and effectiveness (i.e. the quality of access provided) at sub-national scales. In fact, there seems to be no previous attempt of province-level assessment and validation. Hitherto, the focus has been mainly on static snapshots that did not explore the interdependencies of changing demography, growing urbanisation, and nighttime light distribution for electricity access assessment. The relationship between within-country electrification trends, the distribution of wealth within countries, and statistics about appliance ownership represent further unexplored questions. Finally, published studies exploiting nighttime lights to assess electrification have not provided means and code to update results or transpose the analysis to other scales. Today, new and improved satellite data products that are being frequently updated allow for considerably greater precision through improved sensitivity and spatial resolution (Elvidge et al., 2017; Facebook Connectivity Lab and Center for International Earth Science Information Network - CIESIN - Columbia University, 2016; Pesaresi and Freire, 2016). Cloud-computing platforms help leverage these data and make analysis accessible to those without high-performance computational facilities (Gorelick et al., 2017).

In this essay I capitalize on these developments and assess the potential of satellite data to support institutions devoted to tracking electricity access (i.e. progress towards SDG7's target 7.1.1) by complementing and validating a variety of household derived information on electricity access, consumption, and appliance ownership at a community and country-level with a low-cost geospatial indicator that can be updated easily and in near-real-time. To achieve this, I analyse remotely sensed nighttime light radiance data for sub-Saharan Africa combined with georeferenced demographic distribution and settlement type information, and other spatially explicit layers for the period 2014-2019. I estimate sub-national indicators of electricity access inequality that provide insight into the progress towards SDG7 targets at a provincial scale and across rural and urban regions. Crucially, the analysis goes beyond conventional binary measurement by linking electricity use to luminosity to define tiers of access based on the World Bank Multi-Tier Framework (Bhatia and Angelou, 2015). This enables estimating energy poverty even where electricity infrastructure is available. I confirm the recent increase in the pace of electrification in sub-Saharan Africa, with >115 million people gaining access over the 2014-2019 period. Yet, I reveal wide inequalities in the quality of electrification, with a vast distribution across access tiers which cannot be observed in the existing statistics. These results suggest the need to critically evaluate the success of electrification programs beyond their role in boosting the national electricity access statistics.

2.2. Materials and methods

2.2.1. Data inputs and processing

The Google Earth Engine platform (Gorelick et al., 2017) is used to process spatially-explicit imagery and extract data which is used to calculate trends, inequality measures, and to produce plots in the R scientific computing environment. The *Data and Software Availability* section links to the repository that hosts the JavaScript and R and allows for results reproduction, alteration of parameters for sensitivity analysis, and further improvements. All the datasets used in the analysis are openly accessible and retrievable under the references reported in Table 2.1, ensuring full replicability of the analysis.

Table 2.1: Datasets used in the modelling framework

Dataset	**Unit**	**Source**	**Time step**	**Spatial resolution**
High-resolution settlement layer	People	(Facebook Connectivity Lab and Center for International Earth Science Information Network - CIESIN - Columbia University, 2016)	1 year	30 m
Global Human Settlement Layer – built up areas and settlement type layers	Class	(Pesaresi et al., 2013)	5 years	250 m
VIIRS-DNB nighttime light radiance	$\mu W \cdot cm^{-2} \cdot sr^{-1}$	(Elvidge et al., 2017)	1 month	450 m
GADM shapefile	-	(Hijmans et al., 2018)	-	-
DHS surveys	% of people with access	(USAID, 2009)	Multiple years	Province-level
IEA Energy Access database	% of people with access	(IEA, 2019)	1 year	Country-level
Tracking SDG7: The Energy Progress Report database	% of people with access	(IEA et al., 2020)	1 year	Country-level
Atlas of the Sustainable Development Goals from World Development Indicators database	% of people with access	(World Bank, 2018)	1 year	Country-level
ESMAP Multi-tier Framework Surveys	kWh/household/year	(World Bank, 2019a)	1-2 years	Household-level

The data sources include: VIIRS stray-light corrected monthly composites 2014-2019 (Elvidge et al., 2017), the High-Resolution Settlement Layer 30 m ambient population (Facebook Connectivity Lab and Center for International Earth Science Information Network - CIESIN - Columbia University, 2016), and the Global Human Settlement Layer (Pesaresi et al., 2013) – including built up areas and settlement type layers – used for rural and urban areas classification. I select the High-Resolution Settlement Layer as the reference population dataset because it represents the highest-resolution publicly available Africa-wide gridded population layer. This refers to year 2015 and it is based on recent census data and high-resolution (0.5m) satellite imagery from DigitalGlobe. The settlement extent data were developed by the Connectivity Lab at Facebook using computer vision techniques to classify blocks of optical satellite data as settled (containing buildings) or not. CIESN used proportional allocation to distribute population data from subnational census data to the settlement extents. Note that as of late 2019 the HRSL lacks information for four countries in the Horn of Africa: Ethiopia, Somalia, Sudan and South Sudan. I rely on the 250m resolution 2015 GHSL data, downscale it to a 30 m resolution imposing a constraint such that the sum of the pixels remains constant after the downscaling (to avoid generating biased population counts due to the interpolation process), and mosaic it over the HRSL for the four countries in question to produce a comprehensive 30m resolution layer for sub-Saharan Africa. Refer to the *Demographic growth and migration trends* section below describing how the HRSL population counts have been re-projected to previous or following years.

National electrification levels for comparison with my estimates are drawn from the ESMAP/World Bank *Tracking SDG7* portal, i.e. the data underpinning the *Tracking SDG 7 Energy Progress Report 2019* (IEA et al., 2020), the *Atlas of the Sustainable Development Goals From World Development Indicators* database, and the IEA Energy Access database, while province-level figures are drawn from an array of field surveys through the DHS Program STATcompiler (USAID, 2009) for subnational benchmarking. For validating electricity access tiers, World Bank / ESMAP Multi-tier Framework surveys for households are retrieved from the Microdata Library for countries with recent information on the distribution of consumption across urban and rural areas, and this information is used to classify households across consumption tiers. For defining countries and provinces, I adopt the global administrative boundaries (GADM) dataset v3.6 as the standard (Hijmans et al., 2018).

2.2.2. **Identification of urban and rural areas**

Urban and rural settlements are identified at the grid-cell level using the GHS-SMOD 2015 settlements classification to classify populations cells either as urban (GHS-SMOD≥2), or as rural (GHS-SMOD≤1, or as not inhabited (GHS-POP=0). Classification details are detailed in (Pesaresi et al., 2013). In general, urban areas include both cities or large urban areas, i.e. “*contiguous cells with a density of at least 1.500 inhabitants per km^2 or a density of built-up greater than 50% and a minimum of 50.000 inhabitants*” and towns and suburbs or small urban areas, namely “*contiguous grid cells with a density of at least 300 inhabitants per km^2 and a minimum population of 5.000 inhabitants*”. The inhabited pixels that do not satisfy these criteria are marked as rural areas. To assess the consistency of the classification criteria with the country-level urban population share reported by the World Bank (World Bank, 2019b) for year 2018, I sum the total GHS-POP 2015 population in cells classified as urban and divide it by the sum of total population. This yields a regional value of 0.42, which is very much in line with the fraction of urban population in sub-Saharan Africa of 0.4. An exploration of the county-level predicted urbanisation levels reveals that consistency with the World Bank/UN population division figures is mixed across countries. Nevertheless, I deem the remotely-sensed classification of the GHSL more homogeneous than the national figures provided by statistical offices, for which the definitions vary across countries.

2.2.3. **Demographic growth and migration trends simulation**

To estimate the role of demographic growth and migration on the electrification process over the 2014-2019 period considered and implement it into the High-Resolution Settlement Layer gridded population dataset, I adopt an approach relying on the official statistics from World Bank Data over the yearly country-level population growth rate and share of the total population living in urban areas. Algebraically, this can be expressed as:

$$Pop_{\mathrm{t}}^{\mathrm{i}} = U(Pop_{\mathrm{t}-1}^{i\,urb}\left(1 + PGR_t^c(1 + \Delta URB_{t-1}^{t\,c})\right), Pop_{\mathrm{t}-1}^{i\,rur}\left(1 + PGR_t^c(1 + \Delta RUR_{t-1}^{t\,c})\right)) \quad \text{(Eq. 2.1)}$$

where $Pop_{\mathrm{t}}^{\mathrm{i}}$ is the population of pixel *i* in year *t*, $Pop_{\mathrm{t}-1}^{i\,urb}$ and $Pop_{\mathrm{t}-1}^{i\,rur}$ are the urban and rural populations at pixel *i* in the year previous to year *t*, PGR_t^c is the yearly population growth rate in country *c* at year *t,* and $\Delta URB_{t-1}^{t\,c}$ and $\Delta RUR_{t-1}^{t\,c}$ are the rates of change of urban and rural populations, respectively, in country *c* between years *t* and *t-1.* The resulting gridded population layers are therefore given by the union raster layer of the urban and rural populations layers in year *t*, each calculated as the product between the population in each cell *i* and the population growth rate *PGR* in the same year in each country *c* weighted by the change in the share of urban or rural population with respect to the previous year in each country *c*, respectively. The approach allows to integrate the heterogeneity in the demographic change across urban and rural areas and across each country, respectively. The main limit is that – within each country – population dynamics are homogeneous across all urban and rural areas, respectively.

2.2.4. **Electricity access levels estimation and validation**

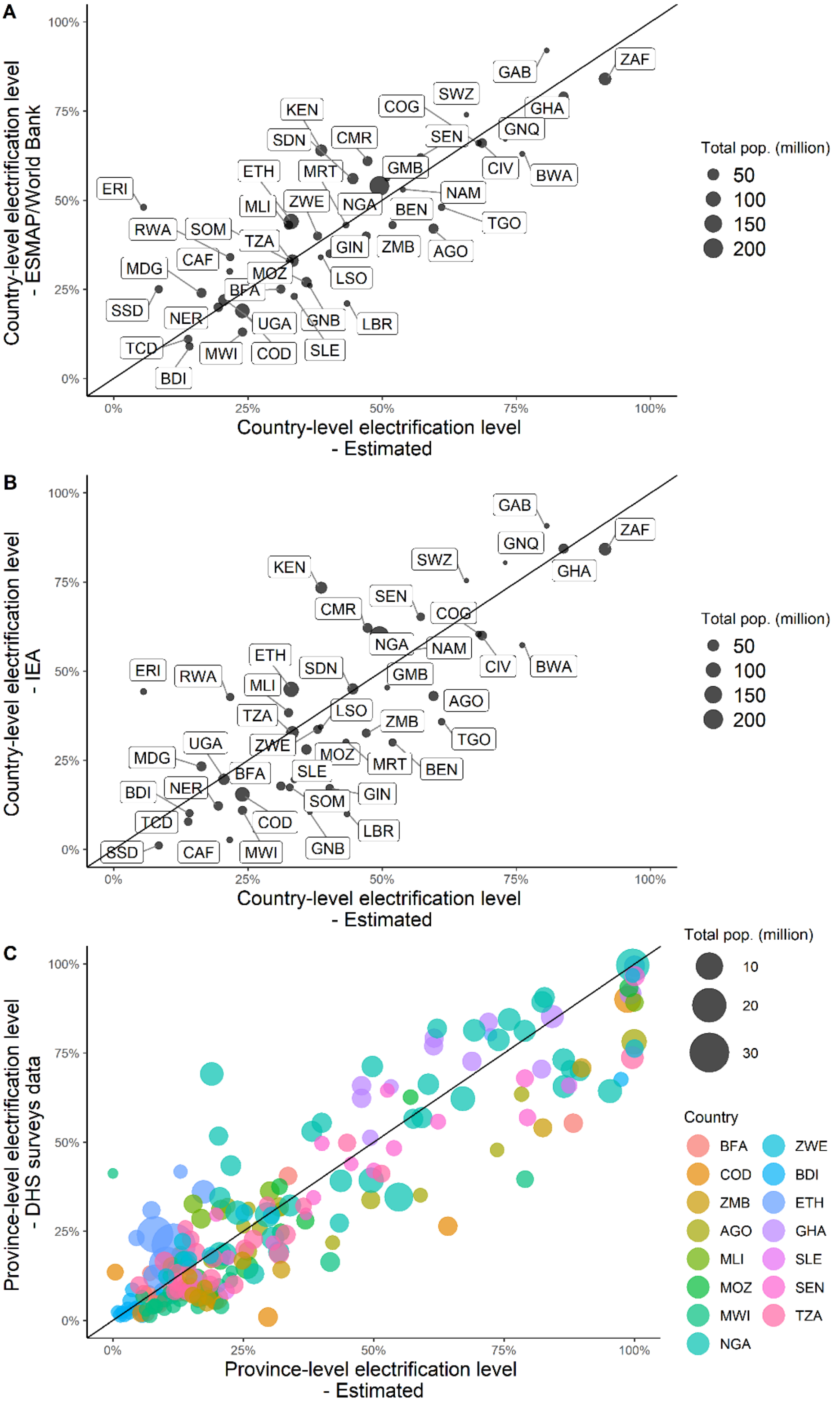

Figure 2.1: Validation plots for the electricity access estimates. Panel A: ESMAP/World Bank data; Panel B: IEA Access Database; Panel C: DHS province-level surveys. Source: Author's calculations.

To estimate electricity access, I calculate the yearly median radiance value in each pixel of the NPP-VIIRS monthly composites within the Google Earth Engine Platform for each year between 2014 and 2019 using Google Earth Engine. Then, to remove calibration noise and ephemeral lights as discussed in the relevant literature (Levin and Zhang, 2017; Román and Stokes, 2015), I apply a lower-bound noise floor (0.25μW $\cdot$cm^{-2} $\cdot$sr^{-1} until 2016 and 0.35μW $\cdot$cm^{-2} $\cdot$sr^{-1} from 2017; see (Falchetta et al., 2019) for a justification of the threshold values choice). I proceed subsetting populated pixels with stable positive radiance and identifying them as electrified, while I classify populated pixels with zero radiance as not electrified. Zonal statistics are calculated within each administrative unit to obtain the sum of the population with access to electricity and total population counts. The ratio between the two numbers is calculated to derive local electricity access levels. To conclude, I validate the estimated electrification levels against an array of sources providing official electrification statistics, as seen in Table Table **2.2** in the *Results* section.

2.2.5. **Measurement of electricity access inequality**

I assess inequality by calculating the Gini index of electricity access among urban and rural areas in each province within each country. The Gini index measures inequality and ranges between 0 and 1, where 0 expresses perfect equality and 1 extreme inequality. In this calculation, provinces are weighted by their (urban or rural) population as a share of the national (urban or rural) population for the Gini index to reflect inequality in terms of the relative number of people in each region. A country with equal electrification levels across its provinces is in fact not equal *per se*, as equality is contingent on the distribution of the population across provinces. Repeating this procedure for the data between 2014 and 2019 allows us to calculate the change in the distribution over the 6-year period examined, as well as the corresponding change in the Gini index of within-country residential access tier inequality. The index is defined as:

$$G_i = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} \left| p_{ic}x_i - p_{ic}x_j \right|}{2n \sum_{i=1}^{n} p_{ic}x_i} \tag{Eq. 2.2}$$

where *x* is the electricity access level and *p* is the share of population of province *i* in country *c*, *j* are all the remaining provinces in the country, and *n* is the total number of provinces. The definition of the Gini index is strictly related to that of the Lorenz curve (Lorenz, 1905), defined as a continuous piecewise linear function *L*(*F*), where *F* that defines the cumulative fraction of the population in the distribution (and is usually represented on the horizontal axis) and L represents the cumulative portion of the total response variable (in this case electricity access) and is plotted on the vertical axis.

2.2.6. **Electricity access tiers estimation and validation**

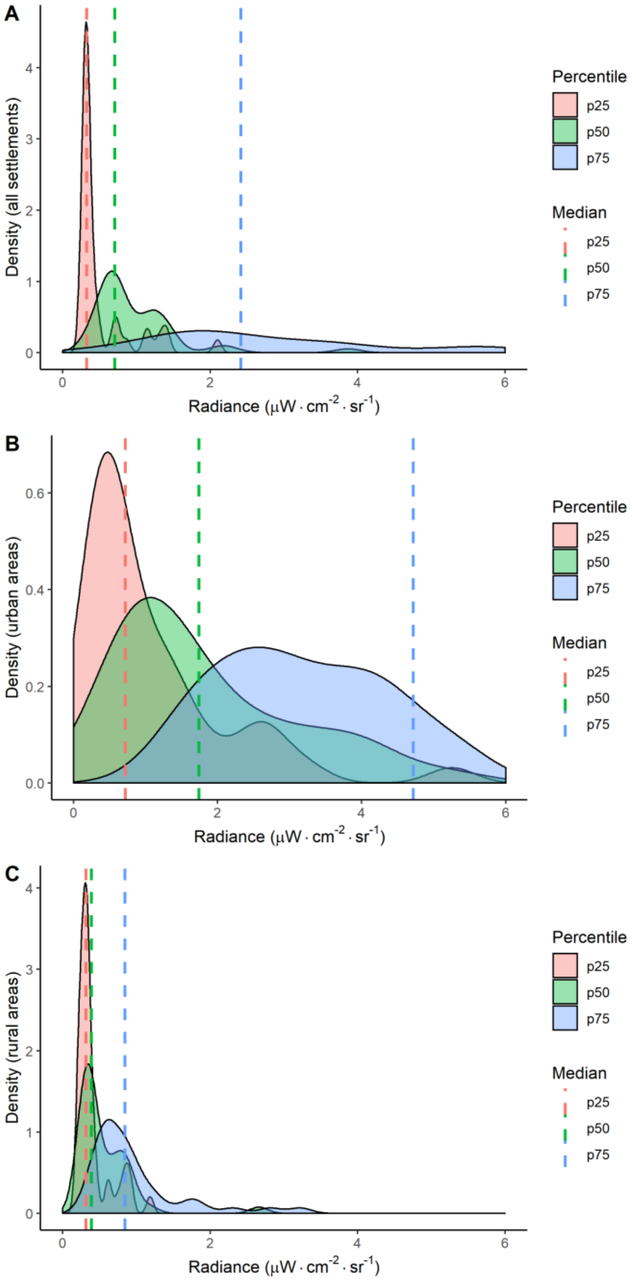

Figure 2.2: Distribution of nighttime light radiance and thresholds identified to define electricity access tiers for national, urban, and rural areas. Source: Author's calculations.

Based on the distribution of the quartile values of non-zero light radiance across SSA countries (Figure 2.2), I define four tiers of residential access to electricity for those estimated to live in areas with electricity access, with thresholds set at the median value of each quartile distribution. To account for the strong urban-rural discontinuity in terms of lighting, this is done separately for urban and rural settlements. I validate the distribution of population across the four tiers against survey data collected from ESMAP in three countries (Rwanda, Ethiopia, and Zambia) where this information is available. These surveys provide a measure of the distribution of households across access tiers in both urban and rural areas. Estimates are thus matched with the World Bank Multi-tier Framework (Bhatia and Angelou, 2015). Here MTF tiers 0 and 1 and 4 and 5, respectively, are considered jointly because the MTF's tier 1 and 5 (<0.2 kWh/household/day and >8.2 kWh/household/day, respectively) corresponds to electricity consumption levels that are either too high or too low to be distinguished from a lack of access or an abundant and reliable level of access.

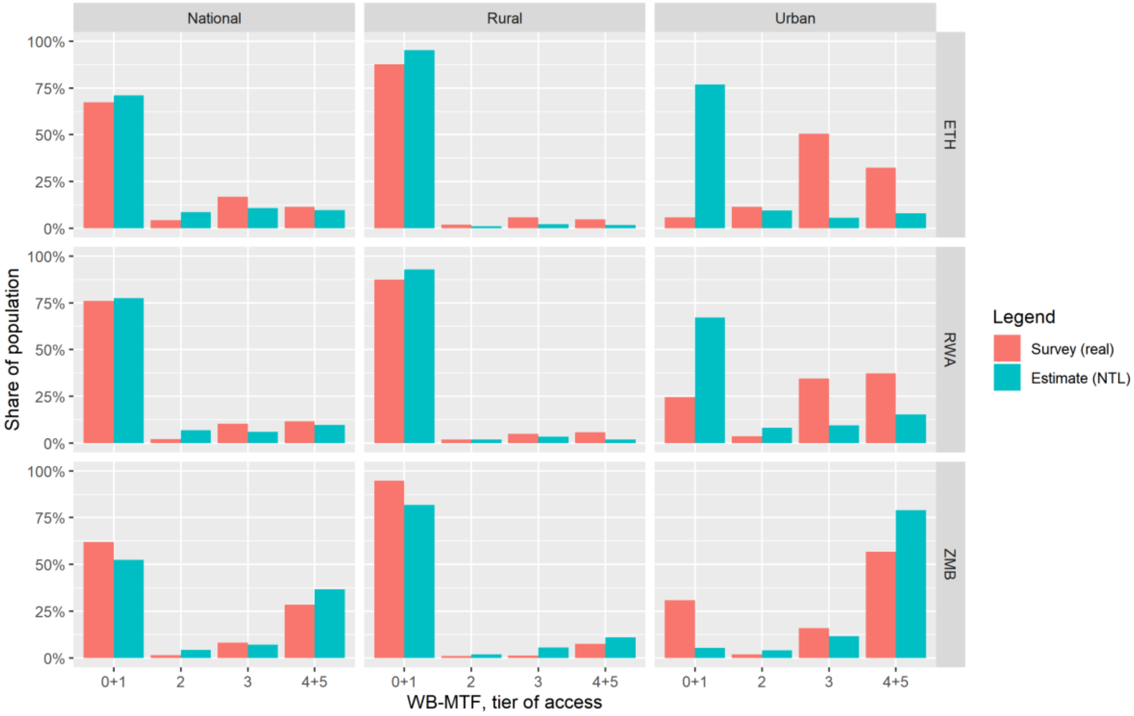

Figure 2.3: Share of the national, urban, and rural population with access to electricity in each access tier according to this paper estimates and the World Bank Multi-Tier Framework field data for Ethiopia, Rwanda, and Zambia. Source: Author's calculations.

2.2.7. **DHS surveys data collation and regression analysis**

To provide a further layer of validation and estimate the relationship between recent progress, the estimated access tiers, and an array of information collected through household surveys, I match province-level statistics on the distribution of wealth across households and information about the share of households owning four basic electric appliances. These are mostly Demographic Health Surveys (DHS) carried out by USAID in the 2014-2019 period analysed. The survey data is provided at a province-level with the province name identifying each observation. Province names are fuzzy-merged with the province names reported in the GADM shapefiles in the R scientific computing environment and linked through a survey-year – estimate-year matching. Then, regression analysis via OLS (ordinary least squares) with the inclusion of country-fixed effects is performed to identify statistical associations.

2.2.8. **Hotspots identification**

To identify hotspots - areas with the fastest growing number of people without access - a regular 10-*km* grid is generated over the shapefile of sub-Saharan Africa. Within each 1-*km* grid cell, I estimate electrification for both 2014 and 2019. The two layers are then subtracted to obtain the difference between the two years, and the number of people without access is summed within each 10-km grid cell. Finally, the grid cells in the top decile (i.e. above the 90*th* percentile of the distribution) are filtered to determine which are classified as hotspot. To assess the location of areas where it is plausible to assume that significant latent demand exists, the electrification level and the mean tier of consumption within each 10-*km* grid cell is calculated. Then, only those grid cells which exhibit an electrification level of at least 50% and an estimated mean access tier lying below the 25*th* percentile of the distribution are retained. To explore the significance of proximity to urban areas for the identified hotspots, I plot pixel-level empirical cumulative distribution curves of the population living in the identified hotspots against the travel time to the nearest 50,000+ inhabitants city. The latter information is derived from (Weiss et al., 2018) and is calculated exploiting a friction surface raster layer that expresses at each pixel the average time to move by one meter given the local road and railway infrastructure, terrain characteristics, and administrative boundaries.

2.2.9. **Electrification rollout requirements calculation**

To estimate the road to full electrification by 2030, I refer to the most recent estimates of population growth from the United Nations Population Division(United Nations, Department of Economic and Social Affairs, 2017). I assume that the newly added population is split among electrified and non-electrified households proportionally to the electricity access rate in 2019. Thus, I estimate the number of people without access in 2030 if the electrification rollout keeps the same pace observed in the 2014-2019 period as:

$$noacc_{2030} = \left(noacc_{2019} + (pop_{2030} - pop_{2019}) \times (1 - el.rate_{2019})\right) - 20 \times 10 \quad \text{(Eq. 2.3)}$$

Where $noacc_{2030}$ is the projected number of people without access to electricity in 2030; $noacc_{2019}$ is the number of people without access to electricity in 2019; pop_{2030} and pop_{2019} are the (projected) regional populations in years 2030 and 2019, respectively. $el.rate_{2019}$ is the share of the population with access to electricity in year 2019. 20 is the historical average number of people who have gained access to electricity every year, and 10 refers to the number of years until 2030. To estimate the average number of people who need to gain access every year to achieve universal electrification by 2030 ($\overline{newacc_t}$), I instead adopt the following formula:

$$\overline{newacc_t} = \frac{\left(noacc_{2019} + (pop_{2030} - pop_{2010}) \times (1 - el.rate_{2019})\right)}{10}$$

(Eq. 2.4)

2.2.10. Mini-grids detection assessment

Before the analysis of the effectiveness of mini-grids, it is imperative to validate the appropriateness of NTL data in capturing electrification occurring through the installation of mini-grids. To estimate electricity intensity in proximity of the mini-grid sites coordinates, we extract the sum of yearly median (noise threshold corrected) radiance value of the VIIRS monthly composites for the years between 2014 and 2019 for pixels falling within the 1000 meter radius buffer around the mini-grid coordinates. The mini-grid database is collected by the African Association for Rural Electrification (CLUB-ER). As part of the Green Mini-Grid Market Development Program (GMG MDP), CLUB-ER in partnership with CARBON TRUST develops a map of the mini-network for 27 countries in SSA. Besides subnational geographical information (i.e. province, region, district, county) and geo-coordinates, the mini-grid database provides information on the capacity of mini-grid (in MW), technology (i.e. hydro, solar PV, diesel), operational status (i.e. not/operating, under construction/project), ownership model (i.e. private, community, public-private partnership), and the year of commissioning. We consider sites as satellite-detected if the NTL measurement is strictly greater than zero. Figure 2.4 displays the percentage of operating mini-grids detected by NTL data for each country covered in the mini-grid database. On average about 70% of mini-grids are captured by the NTL data in the entire sample. There is however quite a large heterogeneity across countries. While Botswana, Ghana and Tanzania rank among the highest with a 100% detection rate, Ethiopia, Mozambique and Zimbabwe rank the lowest with a rate below 20%. The reason for the low rate of detection might be due to the dominance of sparsely populated rural areas in those countries.

To assess whether if estimates can be considered inclusive of mini-grid solutions, I retrieved the only (to my awareness) public georeferenced database of currently operating mini-grid facilities. The data - maintained and published by the World Resources Institute (Odarno et al., 2017)- report all the mini-grids located in Tanzania. Specifically, I test the presence of radiance with a wavelength compatible with that of electric light during the nighttime hours in the 2.5 km radius buffer around the exact coordinate of the mini-grid, when considering the median radiance observed in year 2019 across monthly observations. Irrespective of the limited scope of this dataset, the observation of nighttime light radiance in the proximity of the geographical coordinates where the mini-grid is reported to be installed can be considered a direct empirical confirmation of the successful detection of most mini-grid solutions. In turn, this result provides an interpretative guideline of my electricity access estimates. Namely, it suggests that the estimates are broadly inclusive of populations served by mini-grid facilities. As a result, any residual discrepancy with the official statistics can be attributed to a narrower set of causes, namely: (i) the failed detection of standalone household-level generation solutions by nighttime lights; (ii) the 1000-meter resolution of the nighttime light data and the underlying assumption that in each pixel where electricity use exists everyone is benefitting from electricity access; (iii) biases and statistical growth in the official statistics. As discussed in greater detail in the main paper, questions of the definition of electricity access must be raised.

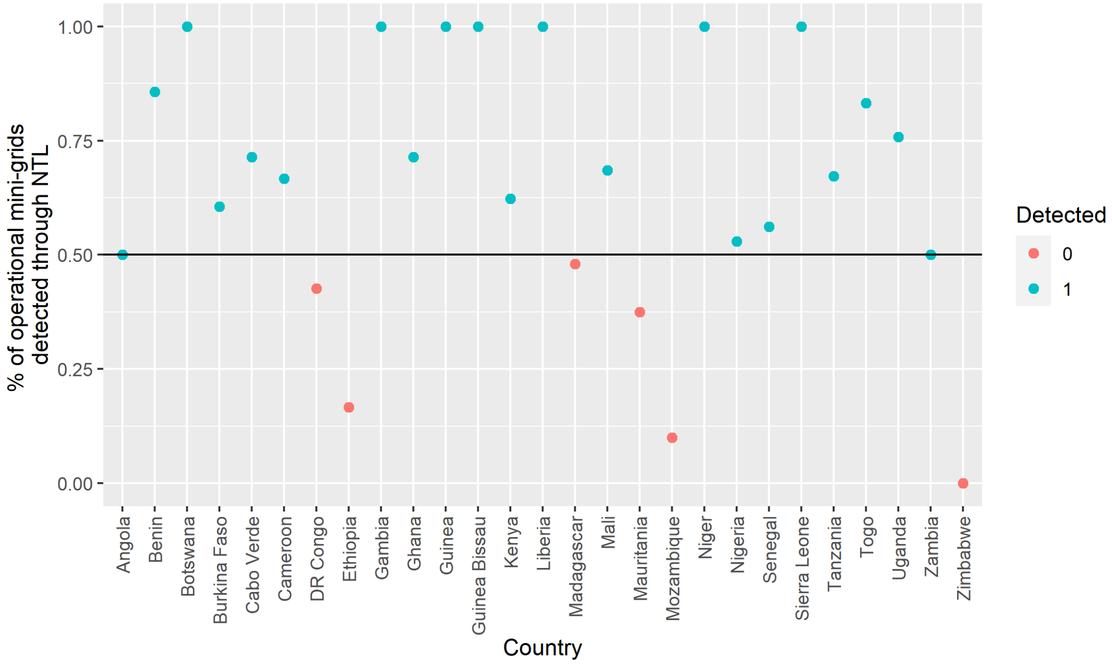

Figure 2.4: Chart reporting the effectiveness of the nighttime light-based methodology to detect operational mini-grid systems in countries of sub-Saharan Africa. Source: Author's calculations.

2.3. Results

2.3.1. Estimates of recent electrification trends

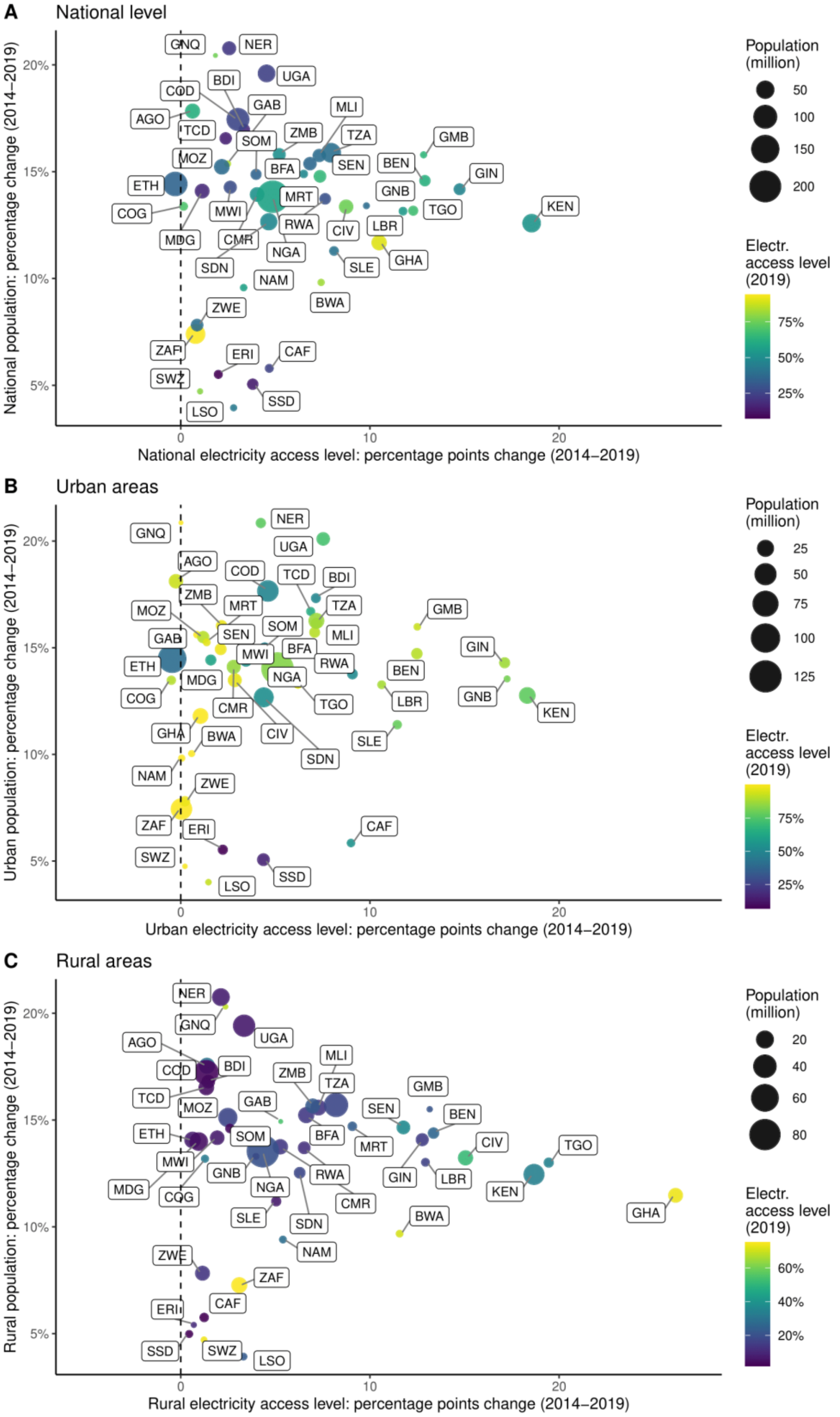

Figure 2.5: Electrification level change (in percentage points) and population change (in relative terms) in sub-Saharan Africa in 2014-2019. Results are grouped at the national

(panel A), urban (panel B) and rural (panels C) scales. Colours describe the electrification level in 2019 (in percentage points), while the size of circles is proportional to the population size in 2019 (in million people). The classification method for urban and rural areas, achieved at a 250m resolution, is discussed in the Experimental Procedures and is consistent with the urbanisation level reported by the World Bank. ISO code labels identify countries as clarified in the codebook in the Appendix. Source: Author's calculations.

A country-level aggregation of the bottom-up high-resolution estimates reveals that over the 2014-2019 six-year period, electricity access in sub-Saharan Africa has grown robustly, with more than 115 million newly electrified people. This has led to about a 5 percentage points increase in the regional electricity access level (growing from 42% to 47%) despite a growing population (by 14%, i.e. +144 million). The remotely-sensed estimates are not dissimilar from the aggregate numbers found in the SE4ALL Global Tracking Framework database, which reports a 6.3 p.p. decline in the share of the population without access between 2014-2017, with the regional electricity access level growing from 38.3% to 44.6%. This represents a significant acceleration with respect to the electricity access growth rates observed in the previous decades (e.g. according to the SE4ALL Global Tracking Framework database, in the 2000-2009 ten-year period the regional electricity access level grew by only 8 p.p.). Potential reasons behind this recent surge may include the momentum created by the introduction of the SE4ALL initiatives and the SDGs, and are discussed in the paper.

Figure 2.5 includes three panels (for national, urban, and rural scales, respectively), each plotting the 2014-2019 progress (in percentage points) of the estimated electricity access levels on the x-axis, and the relative change (in %) in the population over the same time period. The graphs thus depict the trade-off between demographic change (encapsulating both population growth and urban-rural migration; see Experimental Procedures) and electrification rollout. Each country is represented by a bubble, with its size proportional to the total population and its colour describing the estimated level of electricity access level reached at the end of 2019.

When looking at the results at the national level, a picture of a heterogeneous and yet general improvement throughout the continent emerges. The only country where I estimate a quasi-negative electricity access growth is Ethiopia. Ethiopia, Nigeria, and the Democratic Republic of the Congo are in fact the three countries with the largest absolute number of people without access to electricity, accounting together for 231 million people, i.e. nearly 40% of those without access on the continent. In general, I find that countries with the largest rural electrification deficit are characterised by a very fast rural population growth (for instance: Niger, Uganda, the Democratic Republic of the Congo, Chad, or Burundi), which perpetuates a vicious circle that is then reflected in limited national access and progress levels. Conversely, a set of countries showing rapid electrification growth at the national scale also show the highest increases in electrification levels in rural areas, for instance Kenya, Togo, Benin, and Guinea. While rural electrification remains the first concern (with notable exceptions in South Africa, Botswana, eSwatini, and an increasingly improved situation in Kenya, Cote d'Ivoire, Senegal, and Togo), in some countries urban areas are a growing source of concern. For instance, I estimate the urban electricity access level of Ethiopia to have remained nearly constant over the last six years as a result of a near 15% growth of the population living in cities – and therefore an urban electricity access deficit of 56 million people. Other countries with urban electricity access issues include Eritrea, South Sudan, the Democratic Republic of the Congo, Burundi, Sudan, Rwanda, the Central African Republic, and Madagascar. In these cases, migration to cities and population growth dynamics in peri-urban and urban areas are likely to contribute to these trends, nearly out-pacing electrification.

To evaluate the quality of the estimates, I compared them with the most recent available electricity access statistics from multiple sources (see Figure 2.1 for scatter plot comparisons). In particular – as summarised in Table 2.2 – these sources include the *Tracking SDG7: The Energy Progress Report* and the *Atlas of the Sustainable Development Goals* and the *IEA Access*, which reports slightly different country-level figures; and the DHS Statcompiler household surveys (USAID, 2009), through which a multiannual province-level electricity access dataset was compiled including all countries with information available between 2014 and 2019 and then parsed to my province-level estimates for the corresponding survey year. Table 2.2 shows the results of the correlation analysis for the electricity access levels. The results reveal that my estimates are highly consistent with the most recent available yearly estimates (ρ between 0.81 and 0.86) at both the country-level and when assessing provinces within countries. Yet, when evaluating the consistency with the percentage points change, i.e. the improvement in access in recent years, the correlation sinks (ρ between 0.08 and 0.28). That is to say, estimates are consistently in agreement with the latest measurements, but not in agreement for all countries about the improvements that have occurred in recent years.

Table 2.2: Comparison of estimates with multiple electrification statistics databases.

Data source	**Time interval of access**	**Correlation (ρ) with most recent measurement**	**Correlation (ρ) of progress**

	data points		
Tracking SDG7: The Energy Progress Report (2019) / Atlas of the Sustainable Development Goals (2018)	1990-2017	0.86	0.28 (2014-2017)
IEA Access Database (World Energy Outlook 2018)	2000-2017	0.81	0.08 (2010-2017)
DHS Statcompiler household surveys (various years, province-level)	2014-2017	0.82	-

The potential reasons behind the measured discrepancy in the progress and yet the high consistency in the current situation estimates are multiple. First, the nighttime light radiance is a metric of electricity access that is only able to detect electricity use that: (i) is overnight, when the satellite overpass takes place; (ii) is resulting in some form of visible light radiance (which might include indoor and/or public lighting); (iii) has a sufficient intensity to be detected by the satellite sensor, i.e. is above some very low threshold of final use. The implications of this point are discussed in greater detail in the uncertainty and limitations section. From a conceptual point of view, a missed detection of populations with access to electricity (which results in an underestimation of recent progress compared to the official statistics) is likely to be the result of a very low final use, i.e. of a hitherto low effectiveness of electrification. For instance, in those countries where the strongest most recent electrification is reported by official statistics, I observe the greatest discrepancies, namely Kenya, Ethiopia, of the Republic of the Congo, while in many others near-perfect validation is achieved.

Second, and relatedly to the previous point, in related ongoing research I find that populations served by mini-grids are well captured by satellite-imagery but that satellite-based information might not be able to capture standalone decentralised solutions such as household-scale diesel gensets and solar home systems, which have been a strong driver of the recent surge in electricity access level throughout sub-Saharan Africa (Dalberg Advisors and Lighting Global, 2018). Yet, this limitation is linked to the fact that the concept of access to electricity does not have a unique, widely-agreed, definition (see IEA, 2017a). A heated debate over the quantification of the minimum levels of electric energy use deemed necessary to define access is ongoing (Bhatia and Angelou, 2015; Nussbaumer et al., 2012; Pachauri, 2011). One of the crucial arguments is that energy access and energy poverty are not mutually exclusive. At the same time, energy access is not a static concept, but instead should be considered as a dynamic process following a ‘ladder’ (Bensch et al., 2017; Chattopadhyay et al., 2015; Grimm et al., 2016; Monyei et al., 2018), where different technologies and solutions gradually replace the previous ones, providing greater power and supporting more appliances and uses. In this paper, I make an explicit choice in excluding standalone solutions from the definition of energy access because of the very limited amount of energy (and in turn of appliances) they are able to supply (although I acknowledge their role as a first step up the energy ladder (Grimm et al., 2016; Lay et al., 2013), e.g. by saving costs and health burdens associated with kerosene use and allowing for more education through nighttime study and access to telecommunications).

Third, it must be highlighted that inconsistencies and discontinuities across different years are evident in the official statistics. These issues are compatible with the notion of statistical growth, i.e. growth occurring by assumption in the lack of reliable information (e.g., with statistical extrapolations performed by Governments or from development agencies publishing the numbers) or with the deliberate objective of attracting more foreign investment. Refer to the *Appendix*, where the existence of a linear time-trend in official electrification statistics is statistically confirmed, while that of higher-order polynomial relationships is ruled out. Together, these considerations suggest that caveats are required in the comparison with official statistics (which depending on each country's statistical office can include different types of access solutions, including solar lamps or standalone diesel generators) with interannual satellite-based estimates, which are mostly able to capture access through the national grid and mini-grids. Yet, this also implies that the poor results of the recent progress estimates with the official statistics have specific underlying reasons which might not be related to an ineffective methodology, but just to the assumptions it encapsulates and what is actually measured.

2.3.2. Inequalities in sub-national electrification progress

To understand the heterogeneity at the province-level in the recent progress with electricity access, it is crucial to disentangle the interplay between the electrification rollout and the growth in the population without access induced by demography and migration. In Figure 2.6 I map the ratio between the change in the absolute number of people with and without access in each province between 2014 and 2019. The metric suggests the geographic position and density of areas where electrification roll-out has surpassed (or been slower than) the growth in the population without access to electricity. It also indicates provinces where I estimate that no electrification is taking place (no or negative growth in the population with access to electricity) and those areas where – conversely – a negative or null growth in the population without access to electricity was experienced in the period examined. The latter are classified as on a pathway to full electrification. Yet, it must be remarked that they might also identify areas where little electrification has been implemented and yet the electricity access rate has increased due to a decline in the population without access. These situations include provinces experiencing emigration towards other provinces or countries. The analysis reveals significant electrification progress over large parts of Southern Africa (in South Africa, Namibia, and Botswana, and several regions of Angola and Zambia), throughout Kenya and in most provinces of Tanzania and Sudan, and in most West African provinces surrounding the Gulf of Guinea (in Ghana, southern Nigeria, Cote d'Ivoire, Benin, Togo, and Cameroon). At the same time, the map reveals much slower electrification progress in Ethiopia, in most provinces of Central Africa (and chiefly in the Democratic Republic of the Congo), over large parts of Uganda and Burundi, in Chad, and in multiple areas of the Sahel.

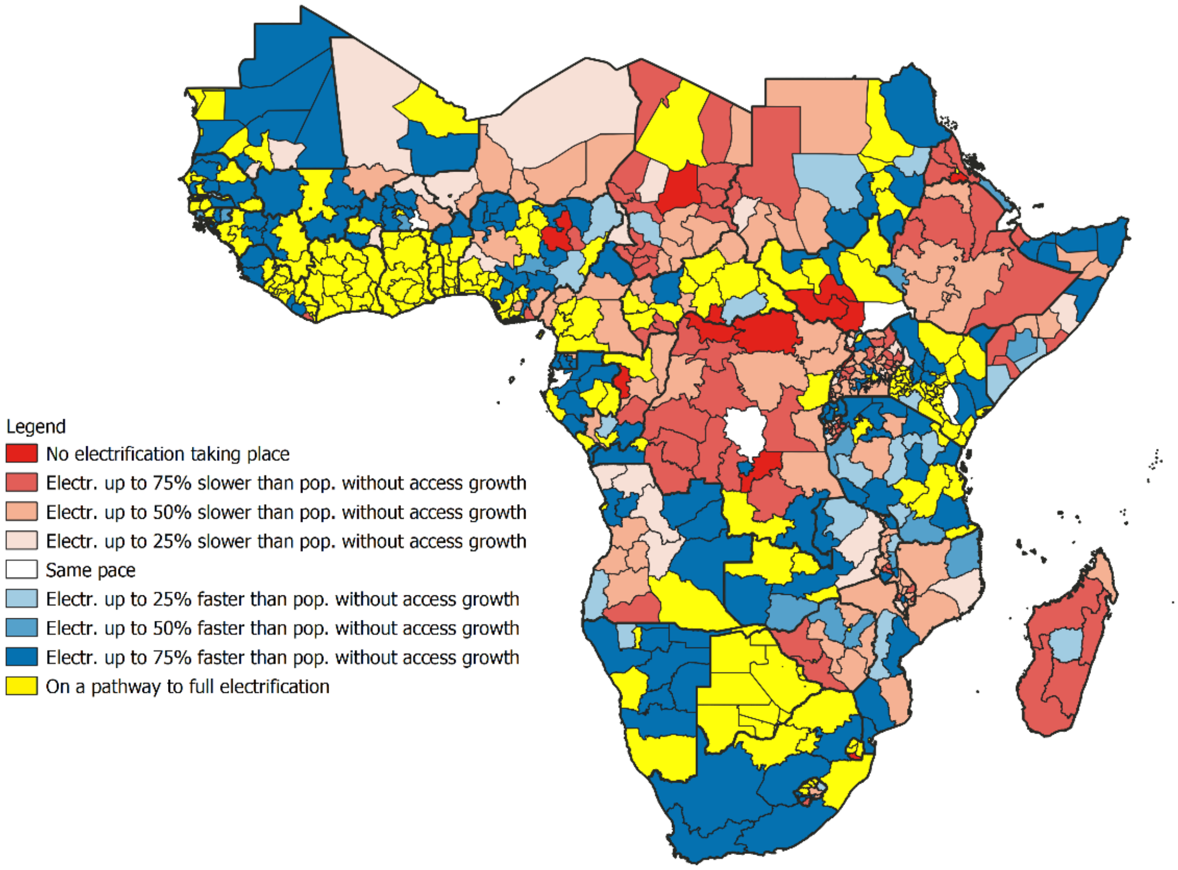

Figure 2.6: Provincial changes in the number of people gaining access and the number of new people with access to electricity between 2014 and 2019. The colour scheme categorizes the data across two dimensions: the growth in the population without access and the growth in the electrified population. Two additional categories identify provinces where the population with and without access have declined. Source: Author's calculations.

The analysis also indicates that in provinces where income is more unevenly distributed, today's electrification access levels tend to be lower (Appendix A tables, model 1). In particular, I find each p.p. increase in the province-level Gini index of wealth inequality estimated using DHS survey data is associated with an average 1.46 p.p. lower satellite-measured local electricity access level (with $P<0.01$). This suggests that these provinces might have historically been less targeted by electrification expansion programs (Trotter, 2016) or even where the grid exists, households in such provinces have had insufficient income to afford connection (Golumbeanu and Barnes, 2013) and running costs, so only few have benefitted from electricity use. On the other hand, there is a likelihood that for those with electricity, they may have become wealthier from having access. In contrast to the results for electricity access *per se*, my province-scale estimates of electrification progress over the last six years are found to be positively correlated (Table A1.1, model 2) with the Gini index of wealth inequality ($P<0.01$). While the magnitude of this association is still very small, close to 0, this result could indicate that in recent years a trend change has occurred, and electrification efforts are now concentrating in areas where today income is more unevenly distributed.

National-scale urban and rural electricity access Lorenz curves for 2014 and 2019, and the forward difference (Figure 2.7) provide further insight into the inequalities in electrification progress. The results show, for example, that in 2014 electricity access inequality was similar in urban and rural areas of Rwanda. Since then, robust progress has been made in the country, particularly among low electrified provinces and rural areas, while urban electrification levels stagnated. Conversely, in rural Kenya progress has been more concentrated in provinces with electrification levels above the second quartile, with a focus on universalizing access in already connected areas and stagnation in several provinces with low access levels. Overall, the select countries represented show heterogeneity in inequality, with unequal distributions in provincial-level electricity access in Ethiopia and the Democratic Republic of the Congo. Calculation of a population-weighted Gini index of electricity access inequality G reveals that while urban inequality in electricity access has been declining throughout countries of sub-Saharan Africa, in rural areas inequality has increased over the six-year period in some countries, e.g. Namibia, Sudan, Niger, and the Democratic Republic of the Congo. The countries with the highest provincial inequality in urban electricity access growth are the Central African Republic, Liberia, Chad, and Uganda ($0.72 \leq G \leq 0.81$). Low urban inequality is found in Rwanda, Sierra Leone and Benin ($0.24 \leq G \leq 0.35$). On the other hand, in rural areas inequality is prevalent in the Democratic Republic of the Congo, Chad, Ethiopia, and the Republic of the Congo (0.65 ≤

G ≤ 0.73). Lowest rural inequality is estimated in Togo, Ghana, Zambia, and Mozambique (0.07 ≤ *G* ≤ 0.21). However, crucially, low inequality may encompass situations where everyone lacks access.

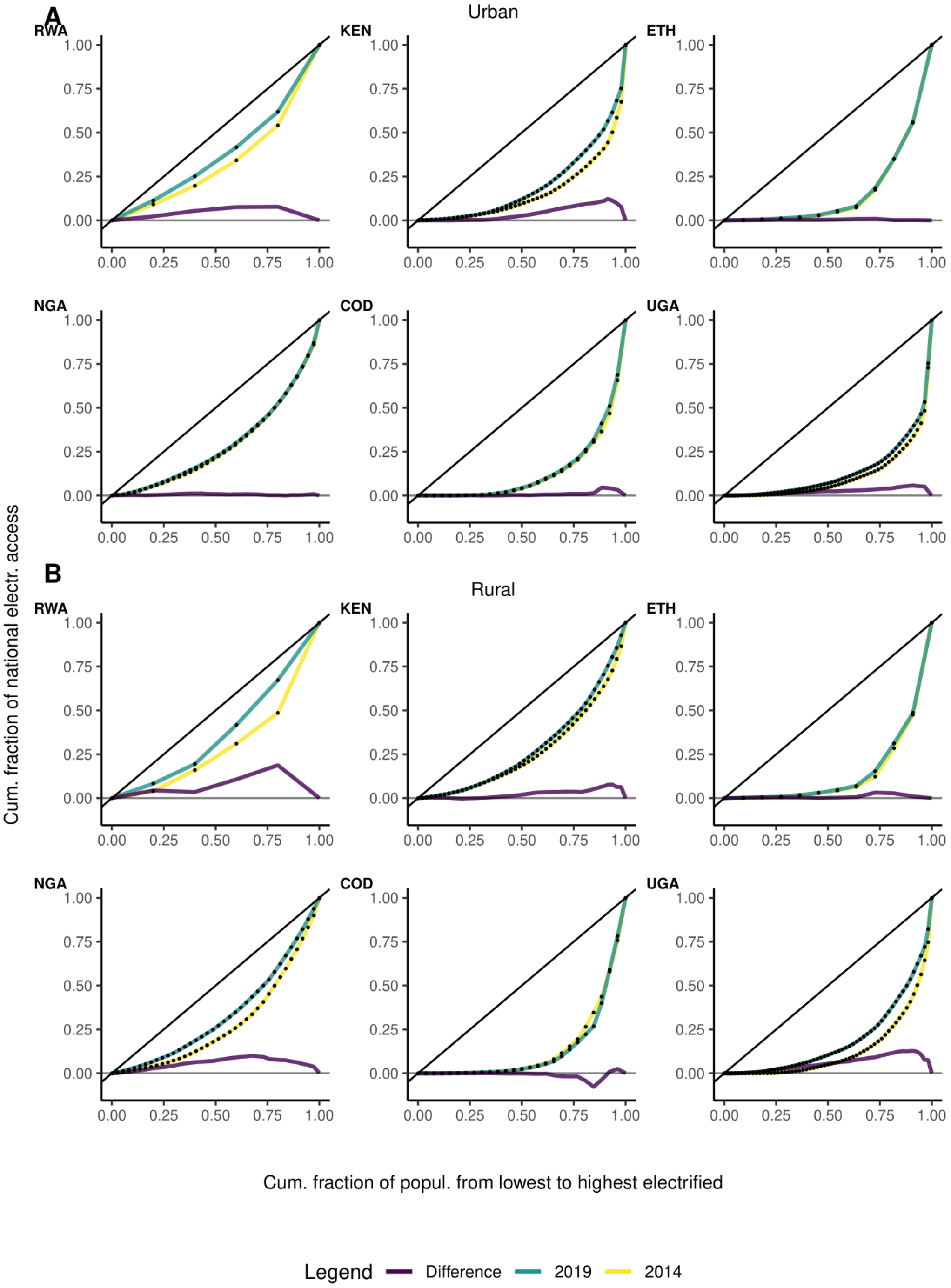

Figure 2.7: Electricity access Lorenz curves for 2014 and 2019, and the forward difference, for selected countries. Results are grouped for urban (panel A) and rural (panel B) areas. The closer the 2014 and 2019 Lorenz curves to the 1:1 line, the lower

the access inequality. Larger spaces between the curves represent greater change between 2014 and 2019, which is also visualized by the red difference curve. Source: Author's calculations.

2.3.3. **Assessing the uneven quality of electrification**

A binary access indicator does not provide any information on whether populations in an electrified area benefit equally from the same level of access (Riva et al., 2018). Recent empirical evidence (Taneja, 2018) has shown that a significant issue related to electricity access expansion is that low consumption levels may persist among those that are connected due to limited power availability and affordability and reliability issues (Blimpo and Cosgrove-Davies, 2019), thus causing a first-order problem for the sustainability of utilities and the development prospects of communities. To distinguish between different levels of electricity use among those that have electricity access, I create four per-capita light intensity categories (see Methodology section and Figure 2.2) to proxy residential electricity use and validate them on recent household survey data building on the World Bank's Multi-tier Framework (MTF) for measuring electricity access quality. In the validation exercise, tiers 0 (no access) and 1 correspond to the MTF's tiers 0 and 1 (i.e. access via pico-scale access solutions) and are grouped together. This is because very low levels of available power, final electricity use, and reliability are here regarded as a lack of access. Conversely, tier 4 is coupled with the MTF's tiers 4 and 5 together, because at higher levels of electricity use nighttime light becomes a marginally worse predictor of final consumption (see (Falchetta and Noussan, 2019) for empirical evidence for this statement). Refer to the Methodology section for a detailed account of the underlying reasoning and data processing steps.

Table 2.3 illustrates the results of the validation procedure, which is carried out for the three countries for which multi-tier data is available thanks to field data collection efforts by ESMAP. These are Ethiopia, Zambia, and Rwanda. As seen more in detail in the by-tier, by-settlement type, and by-country validation plots in Figure Figure 2.3, the method is effective in reproducing the distribution of people among tiers of electricity access reported by ESMAP. In particular, the validation is very precise for the total population and the rural areas in every country, while the main source of mismatch is found in urban areas of Ethiopia – where I underestimate the proportion of people at higher tiers.

Table 2.3: Comparison of access tier estimates with multiple household surveys

Survey	**Surveying period(s)**	**Correlation (ρ) between the distributions for survey data and the NTL-based estimate**
ESMAP MTF Survey Zambia	2018-19	0.92

ESMAP MTF Survey Ethiopia	2017-18	0.65
ESMAP MTF Survey Rwanda	2017-18	0.87

Having provided a proof-of-concept of the general effectiveness of the approach, I generalise the analysis of the distribution of populations among electricity access tiers across all countries in SSA. Figure 2.8 summarises the results of the assessment for national, urban, and rural populations, respectively.

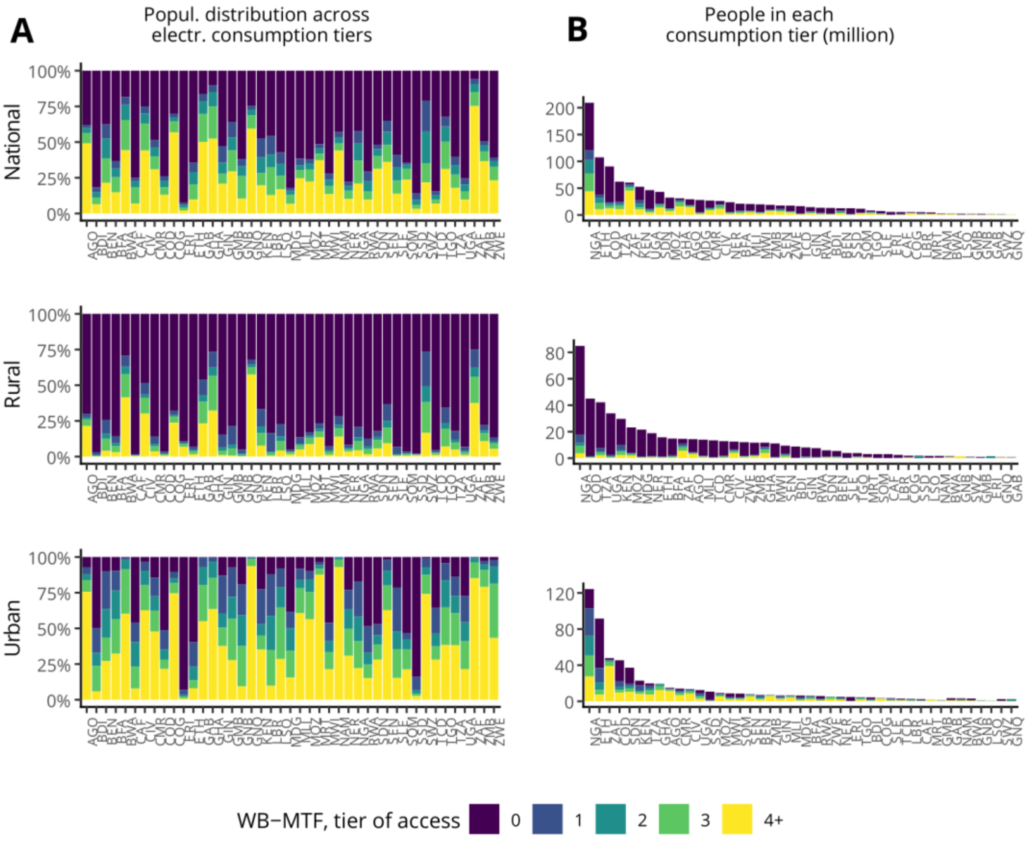

Figure 2.8: Barplots representing the estimated residential electricity access tiers in national, urban, and rural areas. Column A: frequency of population in each tier relative to the national, urban, and rural population. Column B: absolute number of people in each tier for national, urban, and rural populations of each country. Source: Author's calculations.

When examining distributions at a national scale, the assessment reveals that the countries where people with access to electricity are classified among the highest tiers of access include Angola, Botswana, Cote d'Ivoire, the Republic of Congo, Gabon, Ghana, Equatorial Guinea, and South Africa. Lower tier access is prominent among Benin, Ethiopia, Guinea, Guinea-Bissau, Kenya, Liberia, Nigeria, eSwatini, and Togo. In general, countries with large shares of the population at tier 0 of electricity access also exhibit more inequality in the distribution across tiers, with many without access and few concentrated in high consumption tiers (presumably in the main cities, where the bulk of electrified people are located): these include Burundi, the Central African Republic, Chad, the Democratic Republic of the Congo, Malawi, Niger, and Uganda.

Restricting the analysis to urban areas shows that in a large number of countries, most grid-connected consumers benefit from relatively high levels of electricity access. Electricity supply reliability is however an issue in many cities(Cole et al., 2018), irrespective of the average yearly final consumption. Exceptions include – for instance – Burundi, the Central African Republic, Eritrea, Ethiopia, Guinea-Bissau, Liberia, Madagascar, Malawi, Niger, Rwanda, Sierra Leone, Somalia, and South Sudan. In these countries, I estimate that less than 25% of electricity consuming urban households benefit from access at tier 4 or above. Conversely, it is evident how the bulk of the electricity access deficit is in rural areas, with rural access levels below 25% in most countries except the few wealthier nations. In particular, I estimate rural access levels greater than 50% only for Botswana, Gabon, Ghana, Equatorial Guinea, Swaziland, and South Africa. Interestingly, all these countries are characterised by a strong role of the natural-resource extractive sector.

So what about the link between wealth inequality and electricity access? I calculated the province-level association between the estimated average tier of electricity access (obtained by a pixel-level weighted multiplication of population with access to electricity and the local estimated prevalent access tier) and the local Gini coefficient of wealth inequality obtained from the DHS survey data. I control for country fixed effects. The strongly negative result (Appendix A, model 3) shows that an average increase of about 0.21 points in the Gini coefficients is associated with a 1-tier shift in the locally prevalent access tier. This result – albeit not causal – is consistent with assessments in the literature linking electricity use with poverty and inequality[51–56]. The theoretical reasons underlying this empirical finding include the political and economic factors affecting the propensity of policymakers to concentrate their electrification investment towards certain regions (Khennas, 2012; Scott and Seth, 2013; Sovacool, 2012), the uneven load shedding policies which have been shown to disproportionately hurt the poor (Aidoo and Briggs, 2019), and the fact that provinces where there is a high income inequality are more likely to be less electrified – as empirically observed in this paper – and thus the existing distribution grid is likely to be serving only the few rich people, who are also more likely to have electricity through standalone solutions. To provide a further line of validation, using data on appliance ownership, I assess the association between the province-scale estimated average tier of electricity access among people with access to electricity and ownership of different electric appliances derived from the DHS surveys, including radio, mobile phone, television, and refrigerator. The results, summarised in the Appendix A (models 4-7), suggest a strong and positive correlation between access tier and ownership for each of the four appliances. In particular, on average, advancing by one access tier (as estimated with my methodology) implies a 21 p.p., 13.2 p.p., 10 p.p., and 6.8 p.p. average increase (at $P<0.01$) in the propensity of a representative household at province level to own a television, a refrigerator, a mobile telephone, and a radio, respectively. These results provide a further layer of validation to my nighttime-light based approach to assess electricity access multi-dimensionally.

2.3.4. Hotspots of growing access and demand deficits

To identify potential hotspots of high unelectrified population and unmet demand density, I distinguish two types of areas: (i) regions where the latent or unmet demand is likely to rise, i.e. where use remains very low despite relatively high nominal access levels (see Experimental Procedures for details); and (ii) areas that have exhibited the fastest growth in population without access to electricity (Figure 2.9A). Overlaying these two separate regions, helps us to identify five major hotspots: (i) in West Africa, in proximity to the coastal areas of Côte d'Ivoire, Liberia, Sierra Leone, and Guinea (a macro-area hosting nearly 57 million people without access); (ii) in the Gulf of Guinea, over Togo, Benin, and Nigeria (where I estimate 100 million people with no electricity access); (iii) in large parts of Ethiopia and the Horn of Africa (additional 100 million people without access); (iv) across densely populated Burundi, Rwanda, Uganda, and southern Malawi (around 130 million without access); and (v) in the eastern regions of Madagascar (nearly 15 million without access). Other regions with a high density of people without access include the Democratic Republic of Congo and Angola. In addition, regions in West Africa, North-East of Lake Victoria, between Uganda and Kenya, and in Southern Africa include areas with high potential for latent demand growth. These include regions where the number of people without access to electricity has not increased much, but there are several electrified areas with low current use.

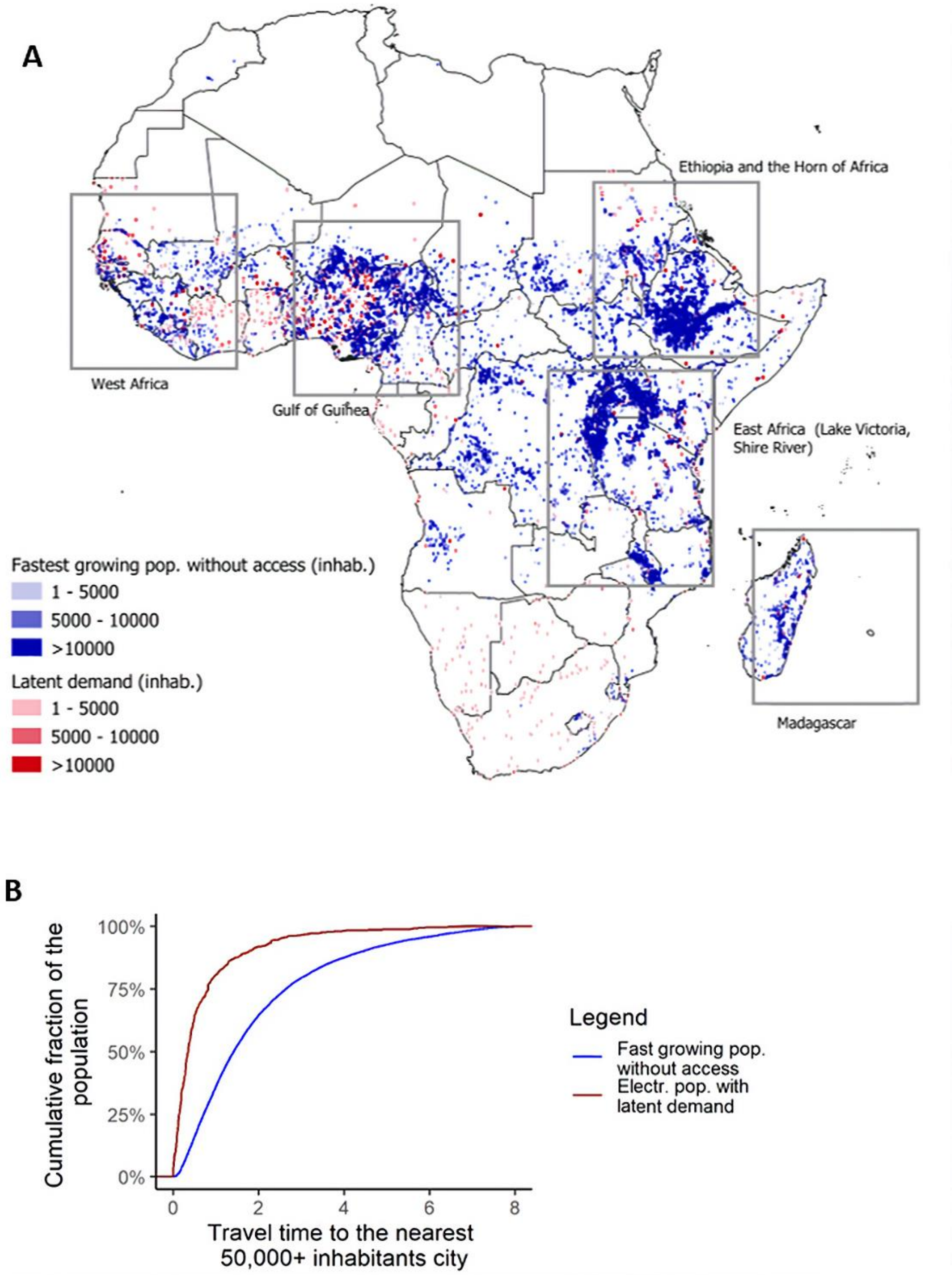

Figure 2.9: Hotspots of growing populations without access and future latent (unmet) electricity demand. Panel A: Map of hotspots in sub-Saharan Africa where rural and urban access hotspots are categorized separately as the top 10% of the respective spatial distributions across all provinces. Urban and rural latent demand hotspots are defined as areas with electrification above 50% but an estimated consumption level below the 25th percentile of the distribution. Panel B: empirical cumulative distribution curves of the fraction of people without access as a function of remoteness to urban

areas in the identified hotspots. The x-axis describes the travel time to the nearest 50,000+ inhabitants city in each country derived from (Weiss et al., 2018). The y-axis describes the cumulative fraction of the population of the hotspot who is living at a travel time equal or smaller to the corresponding x value. The curves thus describe two dimensions of inequality, namely both between and within the selected hotspots. Source: Author's calculations.

Figure 2.9B shows the empirical cumulative distribution curves of the population living in the identified hotspots against the travel time to the nearest 50,000+ inhabitants city. The analysis reveals that more than half of the growth in populations without access between 2014 and 2019 has taken place in settlements that are less than two hours away from the nearest city, while only about 20% of the total are in regions four or more hours away. The picture is even more striking when looking at hotspots of latent demand: I find that over three quarters of these populations are within a one-hour journey to a city, meaning that latent demand among households formally classified as with access to electricity is predominantly a peri-urban issue. Finally, I also observe that the areas that I identify as hotspots of lack of electricity access and latent demand are largely overlapping with areas which are exposed to vulnerability to climate hazards ((Byers et al., 2018)). Recent evidence has suggested a surge in the future demand for cooling (Mistry, 2019) – and in turn for energy (van Ruijven et al., 2019) – in an array of climate scenarios. It is clear that a lack of sufficient, reliable, affordable access to electricity would impair the provision of cooling services, and thus negatively affect socio-economic outcomes, chiefly health (Glaser et al., 2016) and cognitive performance (Kjellstrom et al., 2016).

2.3.5. **Uncertainty and limitations**

An explicit account of the limitations must necessarily supplement studies based on remote-sensing and geospatial data analysis that aim at measuring information that ideally would be collected in the field. While the validation of estimates that are generated in a bottom-up fashion against official aggregates is a first-order approach to quantify potential errors, the specific case under examination – namely developing countries with sparse and infrequent collection of information – is characterised by a substantial degree of uncertainty.

First, I have shown that my approach is likely to capture a substantial share of the electrification occurring through the expansion of national grids or larger-scale decentralised systems, but I are likely unable to detect smaller-scale solutions, such as solar home systems and standalone diesel generators. Yet, the deployment of these is rapidly gaining pace (Dalberg Advisors and Lighting

Global, 2018) and it has been estimated (IEA, 2019) that these could cover around one fourth of new connections until 2030. While these limited-scale solutions are excluded from the definition of energy access that I explicitly adopt in this paper (consistent with the account provided by the IEA in (IEA, 2017b)), they could nevertheless represent a first step up the energy ladder, for instance by saving household costs for kerosene. In turn, at a later stage savings can be spent on larger-scale systems or to cover national grid connection charges (Chattopadhyay et al., 2015; Grimm et al., 2016).

Second, my approach is weak in distinguishing households who live "*under the grid*" and yet are lacking access to electricity, which – in particular in peri-urban areas – represent a significant share of the population (Lee et al., 2016). The spatial resolution of 30 m of settlement data only allows for an assessment of settlements where the infrastructure necessary to provide electricity access is lacking. Thus, a caveat is that this essay's estimates measure the infrastructural dimension of electricity access, more than the policy and financing-related issues that Governments and electrification programs must tackle to enable new connections of households living in the proximity of the grid but facing financial and behavioural barriers (Jacome et al., 2019).

Finally, nighttime lights data largely capture radiance between 0:00 and 4:30 AM, when most residential indoor lights are turned off. Thus, the approach is effective in those settlements where at least minimal amounts of street or public lighting is available (Li et al., 2019). For these reasons, my estimates are correctly interpreted only if considered as a cheap, rapidly updated geospatial indicator of electricity access to provide snapshots of the access situation in a province or in a country, rather than precise estimates of the share of households benefitting from access within a specific village or settlement. Thus, the approach is not meant to replace field data collection efforts, but rather to provide a valuable complement to these efforts. For instance, properly validated satellite-based estimates could help overcome issues of statistical growth when no or infrequent data collection is carried out.

2.4. Discussion

2.4.1. Inequalities in recent electrification revealed

Satellite-based nighttime lights and population distribution datasets allow for analysis of electrification at scales not previously possible and benefit from frequent updates from remotely sensed measurements. I demonstrate that a dataset derived from publicly available global satellite imagery can accurately detect electric light at sub-national scales in sub-Saharan Africa and, more importantly, that light intensity can proxy the tier of residential electricity access, allowing for an estimation of inequalities in electricity supply, use, and reliability beyond binary access indicators. The study provides evidence that these analyses can complement existing survey-based assessments, particularly for regions where data is scarce, sporadically collected, or where there may be inconsistencies in existing data sources. Moreover, unlike household surveys, the approach illustrated here captures rapidly accelerating electrification and changing population settlement patterns in near real-time. The main issues identified are summarised in Table 2.4, together with their spatial extent, and magnitude. Refer to the Appendix A for an ISO code - country name codebook.

Table 2.4: Summary of the main issues identified, their spatial extent, and magnitude

Issue	**Regions**	**Estimated affected population (million)**
High-density electrification deficit hotspots (local access level <25%)	Large parts of East Africa (MWI, UGA, BDI, RWA, SSD, TZA, MDG) and Central Africa (CAF, TCD, COD). Specific areas in MLI, BFA, and ZWE.	300
"Under the grid" electrification deficit hotspots (local access level >50%)	Several countries in West Africa (SEN, GHA, CIV; southern NGA, eastern CMR). Specific provinces in southern KEN, central ZMB, southern NAM, northern SDN.	77
Growth in population without access (2014-2019)	Most provinces of ETH, DRC, COD; large parts of UGA, BDI, TCD; vast areas of the Sahel.	50
Low (tier 1-2) electricity use despite high local access level >50%	Large parts of West Africa (GHA, CIV, SEN, GAB) and Southern Africa (ZAF, BWA); specific areas in KEN, TZA, COD, UGA, MWI, SDN, CMR, AGO, NAM.	70

I highlight that vast disparities characterise electricity access and use within sub-Saharan African nations. In particular, this analysis helps identify and monitor regions where electricity infrastructure provision is not keeping pace with population growth (such as in large parts of Central Africa and of the Sahel), where a high-density of electricity access deficit exists (in Ethiopia, the Gulf of Guinea, and in the countries surrounding Lake Victoria in East Africa), or where use remains very low despite relatively high nominal access levels (such as in rural Ghana and Kenya, or in urban Ethiopia). These results suggest that, even under a scenario where universal access in terms of availability of electricity supply is achieved, inequalities may persist, undermining the achievement of several of the SDGs, and - potentially - driving internal migration. Recent literature (Bayer et al., 2019; Bos et al., 2018; Chaplin et al., 2017; Lee et al., 2019; Lenz et al., 2017; Peters and Sievert, 2016) has highlighted how dimensions other than physical access to electricity, such as reliability, have important impacts on the benefits of access, particularly for small and medium businesses that drive much of the growth in developing countries (Cole et al., 2018; Gannon et al., 2018). The use of light intensity data to derive metrics related to the electricity access tier, as done here, can thus also illuminate important qualitative dimensions of electricity access.

Electricity access and use are key components of a broader, multi-dimensional concept of poverty. Where there are regions of large unmet electricity demand, these are likely to correlate with those deprived of other key infrastructural services for decent living, such as sanitation (2.3 bn. lacking access) (World Health Organization, 2018) and internet connectivity (nearly 4 bn. without access) (Lerner et al., 2017). Not only is a lack of access likely to stunt progress towards other development objectives, but households living in regions deprived of such basics, are also more vulnerable and likely to lack adaptive capacities, essential for reducing risk to natural hazards and climate change impacts (Byers et al., 2018; Castells-Quintana et al., 2018), as aimed by SDG13. Mobile technologies and information services are so pervasive that access to electricity and a smartphone, often achieved long before basic sanitation, opens the possibility of not only life improvements but also vulnerability reduction, through banking, health services, insurance, agricultural training, trading, electoral and social services.

2.4.2. **Potential of achieving full electrification by 2030**

According to my high-resolution estimates, electricity access in sub-Saharan Africa has grown significantly over the last six years, with >115 million newly electrified people. This development resulted in a 4.7 percentage points increase in the regional electricity access level (from 42.2% to 46.9% of the population), despite strong demographic changes (with about 145 million additional people) between 2014 and 2019. However, if electrification rollout in the coming decade keeps the same pace observed in the 2014-2019 period (with an average 22 million new electrified people per year), regional population grows according to the most recent estimates of the United Nations Population Division (United Nations, Department of Economic and Social Affairs, 2017) (thus reaching 1.4 bn. in 2030), and the share of new population that is born without access is assumed to be proportional to the regional electricity access level (see Experimental Procedures), then the regional access level in 2030 will only be 62.5% (16 p.p. above today's level). Thus, to fulfil SDG7's indicator 7.1.1, progress must ramp-up immediately for the coming decade. On average, this implies that almost 75 million people need to gain access each year till 2030, as compared to the average of 22 million/year over the 2014-2019 period.

The underlying trends analysed in this paper reveal that additional dimensions and dynamics must be considered. First, urban and rural areas are changing at different rates, in both electrification rollout and demographic terms. Electrification has moved faster in rural (5.7 p.p. growth between 2014-2019) than in urban areas (4 p.p. growth between 2014-2019) in relative terms, and yet the bulk of progress took place in urban settlements (75 million of the total 115 million who gained access are urban dwellers). Cities are growing rapidly, with the urban population having risen from 540 to 615 million over the six-year period analysed. In turn, high population density and existing distribution infrastructure make it easier and more affordable to increase electricity access in urban areas.

On the other hand, the definition of SDG7 makes only loose mention ("*reliable energy services*" (United Nations, 2015)) to the effective electricity access quality, or to specific power availability targets. This analysis shows that even among households who currently benefit from electricity access, in particular in rural areas, only a fraction benefits from at least tier 3 access, a threshold below which it is challenging to power continuous or medium appliances such as refrigerators or provide air cooling. Previous studies based on computer models have quantified the investment for bridging the electricity access gap in the region (Bazilian et al., 2012; Mainali and Silveira, 2013; Mentis et al., 2017; Pachauri et al., 2013; Szabo et al., 2011; Szabó et al., 2016), showing that there is an abundance of energy resources and local generation solutions, which are technically sufficient to guarantee universal modern energy access in sub-Saharan Africa. However, the required investments and the optimal technology split between national grid connection and decentralised solutions are highly dependent on the modelling assumptions (Morrissey, 2019) (including the level of risk perceived by private players (Milne, 2019) involved in electricity access infrastructure investment) and the assumed demand levels, which – I have shown – needs substantially more consideration in planning towards SDG7.

2.4.3. **Implications for decision-makers**

Sub-Saharan Africa is already witnessing rapid urbanization. This analysis suggests that providing secure, sustainable access even to urban centres with relatively high population densities may be increasingly challenging. Infrastructure expansion in slums is particularly tricky due to the geographical configuration of such areas, legal, regulatory and markets risks for investors (Ahlborg et al., 2015; Onyeji et al., 2012; Trotter, 2016; Williams et al., 2015), and the low ability-to-pay of the peri-urban poor (Golumbeanu and Barnes, 2013; Kojima and Trimble, 2016; Trimble et al., 2016; Vagliasindi, 2012). Focused efforts on identifying best-practices, lessons learnt and barriers in urban electrification roll-out are urgently needed to aid implementation in key locations that are falling behind.

Policies aiming to achieve the SDG7 target of universal electricity access need to facilitate longer-term planning and provide for a decent level of electricity service to all beyond just connections. This requires planning for infrastructure expansion that is commensurate and scalable to subsequent demand growth as incomes rise (Poblete-Cazenave and Pachauri, 2019). Acknowledging the significant geographical dimension to electricity access puts remote regions at a distinct disadvantage(Korkovelos et al., 2019). However, high grid-connection charges, along with other barriers (Lee et al., 2014), can limit the expansion of access, even for households under reach of existing national grids. Overcoming these barriers requires smart payment schemes and innovative business models (Mazzoni, 2019). Challenges with extending central grid infrastructure to remote regions has resulted in an increasing market penetration of decentralized energy solutions that are forecasted to be the least-cost option to bring electricity to households currently without access in many locations across the continent (Dagnachew et al., 2017; Deichmann et al., 2011; Mentis et al., 2017). Care is required in the sizing of such distributed solutions because if under-scaled they may be insufficient to meet growing demand from different sectors and thus exacerbate inequalities, while an over-sizing could make the system economically unsustainable for both users and the companies managing the infrastructure (Blodgett et al., 2017).

Finally, universal access to modern, affordable, reliable, and sufficient energy shows key interlinkages with most SDGs (Nerini et al., 2018), and in particular education (for studying at night, information, communication), health (vaccines storage and medical devices), hunger (food storage and greater nutritional diversity of fresh goods). With regards to SDG13 on climate action (Casillas and Kammen, 2010), previous research has shown that while universal electricity access has very little impact on global greenhouse gas emissions (Calvin et al., 2016; Dagnachew et al., 2018), the electricity requirements for adaptation are instead substantial (Parkes et al., 2019; van Ruijven et al., 2019) and thus need greater consideration in electrification planning. An insufficient supply might leave populations with electricity access exposed to droughts and heat waves, whereas a more resilient and abundant supply could provide the means for essential services, e.g. water pumping and cooling.

2.5. Conclusion

This paper analysed six years of spatially-explicit electrification data for sub-Saharan Africa based on an open-access cloud-computing framework using remotely-sensed sources. My estimates are consistent with previous global analyses, but crucially I show wide hidden disparities of changes in access and tier-measured electricity use within countries and provinces. The analysis confirms that recent progress towards universal electrification has been made, but it shows that nominal access levels are inherently limiting. Focusing solely on maximising nominal access levels might even jeopardise the achievement of other SDGs, because connections alone do not ensure actual use of electricity, reduce related inequalities, or help achieve co-benefits across several other SDGs.

Crucially, I find that among those with access to electricity, a vast distribution across access quality tiers exists. I also find that in some countries, where recently strong electricity access growth (the main ones being Kenya and Ethiopia) has been reported, the estimated final use remains very limited among newly electrified households. This is consistent with previous studies finding e.g. that per-grid-connected domestic customer power consumption in Kenya has declined by almost 70% over the last ten years due to the very low consumption of newly connected customers (Taneja, 2018), and that recent large-scale national grid electrification investment in Rwanda has hitherto led to very low use of newly connected households, with a median of 6 kWh/month and limited appliances uptake (Lenz et al., 2017).

Together, these results raise questions over the effectiveness of those electrification plans and suggest the need to critically evaluate the success of electrification programs beyond their role in boosting the national electricity access statistics. This implies that large gaps in unmet demand might remain both across and within countries even under a scenario of universal electrification by 2030. In turn, this unequal service provision could have serious implications for achieving nearly all SDGs, including SDG10 that specifically targets the reduction of inequalities, and SDG13 since energy poverty limits the capacity of households and productive facilities to adapt to a changing climate (Mastrucci et al., 2019; van Ruijven et al., 2019), constrains access to health and education services (Bos et al., 2018; Kanagawa and Nakata, 2008), and it might affect food security (McCollum et al., 2018) Moreover, I estimate that if the electrification pace witnessed in the last six years remains constant, in 2030 the progress to full electrification in sub-Saharan Africa would be only about 63%, leaving 520 million still without access. This means that progress must ramp-up in the coming decade, and on average 75 million people must receive access to electricity each year until 2030. I have shown that the strong demographic growth and migration flows play a very significant role in this process.

I argue that electrification projects and monitoring initiatives need to consider a broad array of aspects and implications of electrification, and not focus exclusively on maximizing electric connections alone. Insufficient power might leave many households without the capacity to benefit from productive uses of energy, or to adapt to new conditions, even when they are formally classified as with electricity access. To this end, properly validated satellite-based estimates can be an effective, readily-updated, and low-cost means to complement surveying efforts targeted at tracking electrification progress and planning its expansion.

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3. M-LED: multi-sectoral latent electricity demand assessment for energy access planning

3.1. Introduction

Electricity is a direct input to virtually every economic sector. An abundant, affordable, and reliable provision of power is a necessary condition for human livelihoods to thrive. This involves the achievement of nearly all the UN Sustainable Development Goals (SDGs) (McCollum et al., 2018; Nerini et al., 2018). Recent statistics on electricity access show that globally just under 800 million people (about 10% of the global population) live without access to electricity, more than two-thirds of which are in sub-Saharan Africa (IEA et al., 2020). Even in areas reached by electricity infrastructure, a large latent demand often persists (Fabini et al., 2014; Falchetta et al., 2020; Poblete-Cazenave and Pachauri, 2019).

In the context of energy planning to eliminate energy poverty, the assessment of the long-run electricity demand plays a crucial role (Leea et al., n.d.). Namely, the choice of the most efficient electricity supply option and the size of the local generation capacity and storage system strongly depend on the assumed local demand. In turn, this demand is defined both by the hourly load curve and its peaks, and by the total energy consumption. The link between the target demand and electricity supply planning becomes very evident when carrying out country or regional scale studies with Geospatial Electrification Models (GEMs). GEMs are data-intensive computer-based tools that can support policymakers in the integrated evaluation of the most suitable and cost-effective technology for providing electricity access to all settlements (Adkins et al., 2017; Cardona and López, 2018; Kemausuor et al., 2014; Korkovelos et al., 2019; Mentis et al., 2017; Moner-Girona et al., 2019, 2016; Morrissey, 2019; Ohiare, 2015; Parshall et al., 2009; Sanoh et al., 2012; Szabo et al., 2011; van Ruijven et al., 2012). Thanks to growing data collection and management facilities, bottom-up techno-economic electrification analysis has become widely available (refer to the *Global Electrification Platform* and the *WRI's Energy Access Explorer*). Differently from approaches based on linear programming, GEMs do not aim at locally optimising energy systems for specific communities. Their main characteristic is that they allow to identify – country or region-wide – the optimal set-up (i.e. the technology with the lowest local levelized cost of electricity) for providing electricity access at each settlement, along with the generation capacity and investment requirements. The cost-optimal set-up depends on the local energy resources and existing infrastructure.

Yet, most of the GEM-based literature has been strongly supply-side oriented (Morrissey, 2019). Studies have focused mainly on residential energy services when defining the demand of settlements lacking electricity access, and have so far exhibited limited capacity of accounting for the electricity demand from services and productive uses driven by the presence of farms, small businesses, commercial activities, healthcare facilities, and schools. In these studies, the residential demand itself has mostly been calibrated with regional average residential electricity consumption levels of urban and rural consumers (Mentis et al., 2017; Szabo et al., 2011; Szabó et al., 2016; van Ruijven et al., 2012), with little within-country heterogeneity. Archetypical demand targets include – for instance – values for sub-Saharan Arica from the World Bank Multi-Tier Framework (Bhatia and Angelou, 2015) or specific per-capita consumption levels defined by decision makers under a medium-run time horizon (usually 2030, the Sustainable Development Goals target year).

Many studies exploiting GEMs based on such top-down characterisation of the demand have concluded that decentralised energy solutions will play a prominent role in guaranteeing that SDG 7.1.1 (the universal electricity access target) is met. For instance, the Africa Energy Outlook 2019 (IEA, 2019) argues that mini-grids and stand-alone systems will serve 30% and 25% of those gaining access, respectively. This means that for more than half of the households, the electricity access problem could be solved thanks to decentralised energy technologies. Yet, care is required in the interpretation of these results. The number and size of non-residential consumers in a community can have a crucial effect (Peters et al., 2019) on the total long-term energy demand, the peak loads, and consequently a direct effect on the optimal energy technology mix (diesel generator, PV, wind, biomass, hydro or hybrid technologies), on the optimal technology set-up (i.e. the choice between grid extension, mini-grid, or standalone solutions) and on the overall cost-benefit analysis of electrification ("A New Nexus Approach to Powering Development," 2020; Brüderle et al., 2011; Morrissey, 2018). An inadequate or generic formulation of the demand might lead to inefficient allocation of budget and sizing of electricity infrastructure (Riva et al., 2019). Moreover, enabling services for the community and productive uses of electricity beyond basic household needs – such as energy use in agriculture, small businesses, and healthcare and education facilities – is crucial to unleash local economic development (Riva et al., 2018). While substantial uncertainty persists over the structural welfare impacts of household electrification programs (Urpelainen, n.d.), there is robust evidence of the positive effect of electricity provision on time spent by household members in income-generating activities (Bernard, 2010; Bos et al., 2018; Rathi and Vermaak, 2017; Van de Walle et al., 2013). In turn – provided a set of conditions is satisfied – the electricity input might improve the income of the whole community (Peters and Sievert, 2016).

Different approaches have been introduced so far to tackle these limitations. For instance, the adoption of more detailed and heterogeneous household consumption profiles (Trotter et al. 2017), the use of system dynamics (Riva et al., 2019), or the life-cycle assessment of embodied energy in goods and services that contribute to providing what is defined *decent living energy* (Rao et al., 2019). Yet, only few (Moner-Girona et al., 2019, 2016; Narayan et al., 2018; Zhang and Zhang, 2019) of the existing GEM-based studies have so far taken into consideration field-validated load profiles or accounted for the existence of services and productive activities to estimate local energy demand requirements. To tackle these challenges, it has been argued that planning tools need to be improved, and evidence-based projections of electricity consumption need to be used (Blodgett et al., 2017; Moner-Girona et al., 2018). The main roadblock to deliver a standard methodology to estimate electricity demand stems from the data-intensiveness of the estimation, the uncertainty over the quality of the existing data and about the different scenarios that forecast the energy demand growth over time, as well as the computational challenge to produce a high-resolution output.

To advance the state-of-the art in the characterisation of the demand for electricity and ensuring that insights drawn from GEMs are suitable to empower communities in the context of electrification planning, here we introduce the open-source Multi-sectoral Latent Electricity Demand (M-LED) geospatial data processing and assessment platform, developed and maintained by FEEM and the Polytechnic University of Milan. M-LED enables an estimation of electricity demand in communities that live in energy poverty. The key novelty of the platform is its multi-sectoral, bottom-up, high spatio-temporal resolution evaluation, which altogether advances the state-of-the-art on latent electricity demand characterisation. Here, by latent demand, we refer to demand which would exist if the infrastructure and techno-economic conditions to supply it would be met. Secondly, besides modelling different non-residential sectors including the agriculture, service, and productive activities, the platform includes a more detailed assessment of residential demand – representing heterogeneous appliances ownership and usage patterns and allowing for stochastic variability in the demand. Thirdly, the M-LED platform enables a characterisation of the seasonal and hourly variation in the demand from different sectors is of crucial importance for properly planning the energy system and assessing the complementarity of variable renewable energy sources supply curves with the demand. Finally, the multi-sectoral approach includes an assessment on the water-energy needs and the nexus implications for agriculture-related activities. This encompasses an analysis of the potential revenues and costs from the potential agricultural productivity growth thanks to artificial irrigation as a result of the provision of electricity.

The remainder of the paper is structured as follows. Section 2 introduces the methodology of the M-LED platform to carry out the multi-sectoral, bottom-up, high spatio-temporal resolution electricity demand evaluation. Section 3 presents an application of the platform for country-study of Kenya. Section 4 discusses the relevance of the results and highlights potential future applications of the M-LED platform.

3.2. Materials and methods

3.2.1. The Multisectoral Latent Electricity Demand assessment platform

An integrated electrification plan must identify and target population catchment areas (in this study defined as *clusters*; refer to the Appendix 2) and the different local electricity consumption drivers. These include residential demand, productive activities, and several service-provisioning facilities. The M-LED platform is an open-source, bottom-up platform designed to characterise power requirements across different sectors. The platform combines openly available geospatial information, modelling instruments, and scenario analysis to support a sectoral-inclusive electrification planning (see the Appendix 2 for a detailed description of the underlying Materials and Methods). The input data sources are openly accessible and are reported in Table A2.1. The data processing procedure collates field and remotely sensed observations. The lack of data or uncertainty over future evolutions over certain sectors is tackled with explorative modelling. Figure 3.1 offers an overview of the workflow. The methodology is based on an array of Python-based open-source GIS algorithms (from Quantum-GIS, GRASS-GIS, SAGA-GIS, and GDAL) complemented by intermediate R scripting.

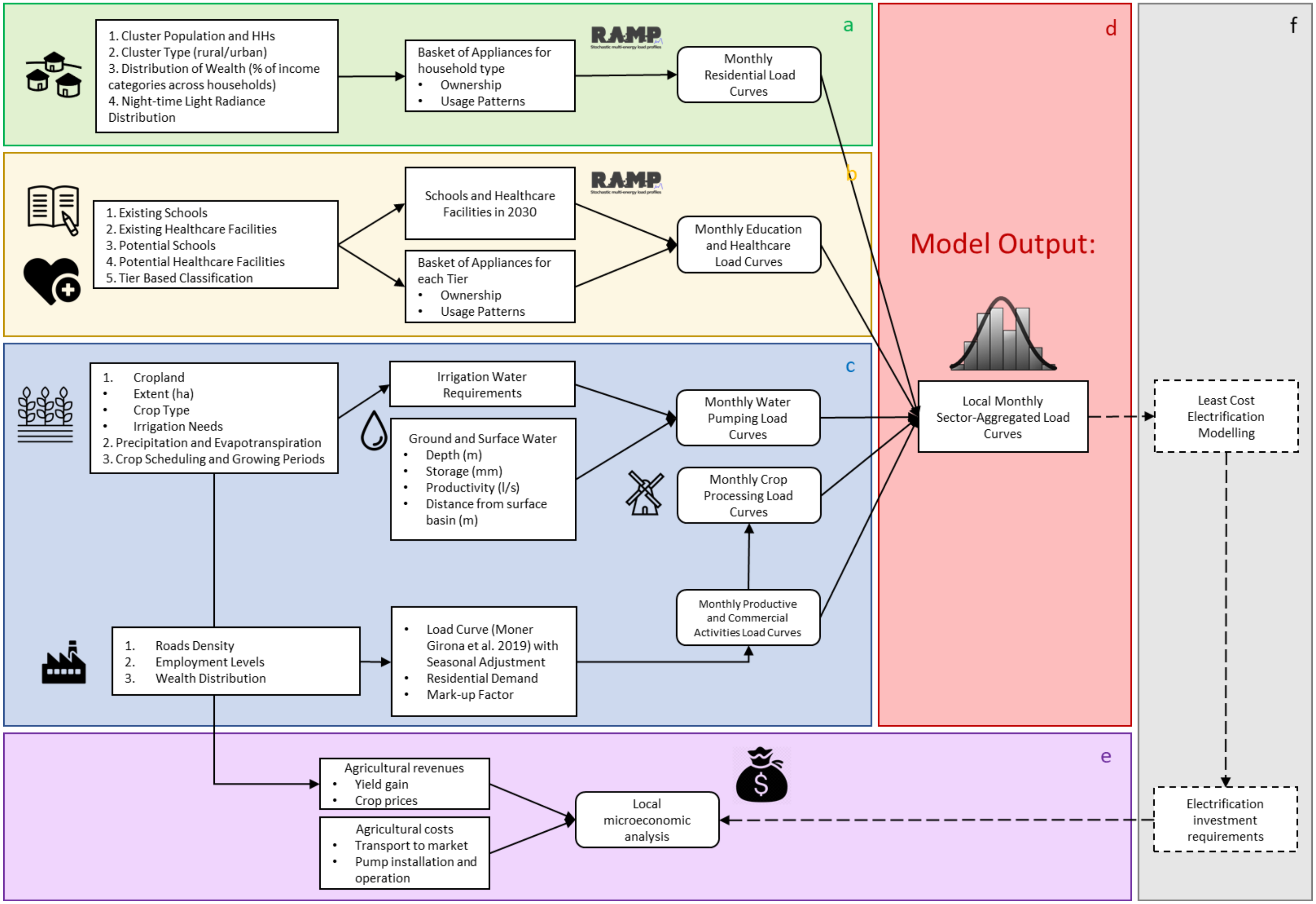
a
1. Cluster Population and HHs
2. Cluster Type (rural/urban)
3. Distribution of Wealth (% of income categories across households)
4. Night-time Light Radiance Distribution
Basket of Appliances for household type
• Ownership
• Usage Patterns
RAMP
Monthly Residential Load Curves
b
1. Existing Schools
2. Existing Healthcare Facilities
3. Potential Schools
4. Potential Healthcare Facilities
5. Tier Based Classification
Schools and Healthcare Facilities in 2030
Basket of Appliances for each Tier
• Ownership
• Usage Patterns
RAMP
Monthly Education and Healthcare Load Curves
c
1. Cropland
• Extent (ha)
• Crop Type
• Irrigation Needs
2. Precipitation and Evapotranspiration
3. Crop Scheduling and Growing Periods
Irrigation Water Requirements
Ground and Surface Water
• Depth (m)
• Storage (mm)
• Productivity (l/s)
• Distance from surface basin (m)
Monthly Water Pumping Load Curves
Monthly Crop Processing Load Curves
1. Roads Density
2. Employment Levels
3. Wealth Distribution
• Load Curve (Moner Girona et al. 2019) with Seasonal Adjustment
• Residential Demand
• Mark-up Factor
Monthly Productive and Commercial Activities Load Curves
d
Model Output:
Local Monthly Sector-Aggregated Load Curves
f
Least Cost Electrification Modelling
Electrification investment requirements
e
Agricultural revenues
• Yield gain
• Crop prices
Agricultural costs
• Transport to market
• Pump installation and operation
Local microeconomic analysis

Figure 3.1: Conceptual framework of the M-LED platform. (a) Residential demand: clustering and appliance baskets generation and parsing; (b) Healthcare and educational demand: geolocation and classification of facilities and appliance baskets generation and parsing; (c) Agricultural uses (irrigation and crop processing) loads (see Figure 3 for further details), micro enterprises and commercial demand: drivers of energy demand assessment and sectoral demand calculation; (d) Model Output: Cluster and Sector -specific yearly Load Curves with month level seasonality and 1-hour resolution. (e) Assessment of costs and revenues of increased agricultural productivity. (f) The produced output is intended to be fed in geospatial electrification models for more effective energy planning: this is not included in the present work. Source: author's elaboration.

The platform exploits the RAMP (*Remote-Areas Multi-energy systems load Profiles*) model (Lombardi et al., 2019), which supports the creation of stochastic, seasonal-heterogeneous energy demand profiles. The underlying stochastic process lies in the structure of the bottom-up model adopted for load profile generation (Figure 3.2). The structure consists of three different layers of modelling: the *User Type*, the *User* and the *Appliance* layer. "*The first layer consists in the definition of a set of arbitrary User types (e.g. Household, Commercial activities, Public offices, Hospitals, etc.). Each User Type is subsequently characterised in terms of the number of individual Users associated to that category (second layer) and in terms of Appliances owned by each of those Users (third layer). The three-layer structure allows to independently model the behaviour of each jik-th Appliance, so that each individual ji-th User within a given i-th User Type will have a unique an independent load profile compared to the other Users of the same Type. The aggregation of all independent User profiles ultimately results in a total load profile, which is uniquely generated at each model run. Multiple model runs generate different total load profiles, reproducing the inherent randomness and unpredictability of users' behaviour and allowing to obtain a series of different daily profiles*" (quoted from ref. (Lombardi et al., 2019)).

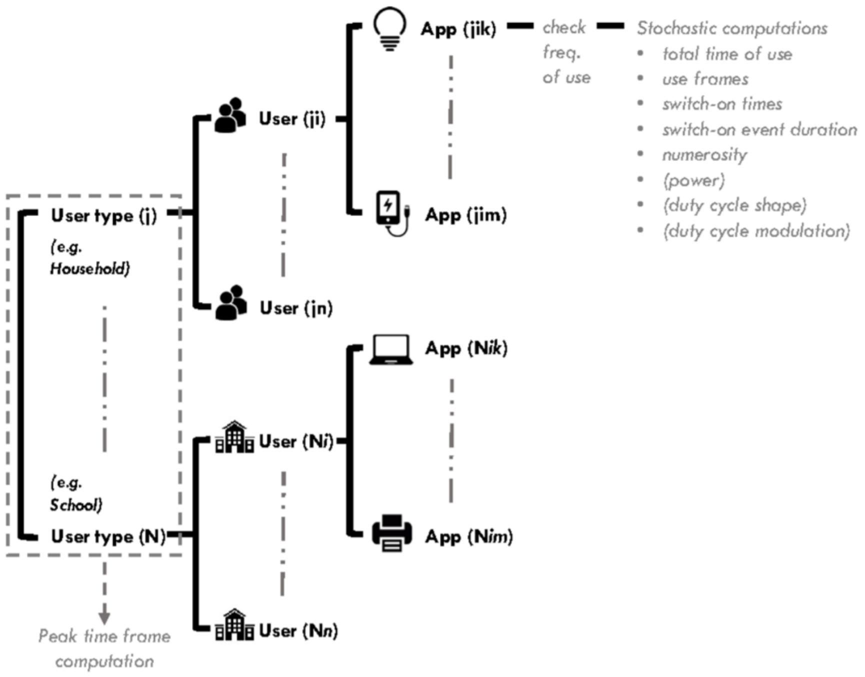

Figure 3.2: Schematic framework of the RAMP stochastic load generation model. Source. Lombardi et al. (2019).

The M-LED platform generates instantaneous electricity demand load curves (rendered at a one hour time step) and then derives the monthly (seasonal-varying) and yearly-aggregated consumption levels. The outputs consist of georeferenced layers for the estimated latent (i.e. currently unsupplied) electricity demand within population clusters from a set of residential, productive activities, and services. Residential, health, and education load profiles are computed following a probabilistic distribution starting from field campaign or literature-validated appliance ownership and use patterns under an array of scenarios. Agricultural (irrigation and crop processing) and micro enterprises loads are assessed combining techno-economic modelling and literature estimates.

An applicative example for Kenya is provided (with accurate country-specific data and a comprehensive assessment on the water-energy needs for agricultural activities). The key added value of the M-LED methodology is that its results will allow carrying out supply-side planning of energy access systems according not only to the energy resource availability but also to the local specific community and productive load profiles, including daily, weekly, and seasonal variation, which can significantly affect system design (Huld et al., 2017). On top of that, the M-LED geospatial analysis allows to identify agricultural productivity growth hotspots where investment can be prioritized to leverage the strongest welfare impact. For instance, the platform estimates the increase in the revenues from the potential boost in the per-hectare yield due to artificial irrigation, which in turn might compensate for the low ability-to-pay for energy services of rural dwellers (Blimpo and Cosgrove-Davies, 2019).

The code and data for the M-LED platform are hosted at the public repository https://github.com/giacfalk/M-LED, which also includes a maintained documentation at https://github.com/giacfalk/M-LED/wiki.

3.2.2. **Residential, services, and micro-enterprise loads**

Residential electrification plays a crucial role for human wellbeing, for instance by enabling telecommunications, conserving food fresh, indoor air circulation and cooling, and night-time activities. In fact, most electrification efforts and targets, including SDG 7.1.1, focus on bringing electricity to all households. Yet, also a large number of healthcare and education facilities face significant constraints in their activity because they are unable to operate appliances that are crucial for guaranteeing the wellbeing and development prospects of local population (Adair-Rohani et al., 2013; Sovacool and Vera, 2014). Finally, the provision of electricity can foster small entrepreneurial activities such as small shops, mini-markets, handcraft and telecommunication services retail (Bose et al., 2013; Kariuki, 2016; Manggat et al., 2018) which can represent a significant leverage for broader socio-economic development (Kongolo, 2010).

With regards to residential electrification, to tailor infrastructure efficiently it is necessary to distinguish among different household types. A relevant example is the introduction of ESMAP's *Multi-Tier Framework for Measuring Energy Access* (Bhatia and Angelou, 2015). To estimate household demand in a flexible way, the M-LED framework is designed to ensure a large degree of heterogeneity in residential power demand. We construct 5x2 = 10 archetypical types (five in urban areas, and five in rural settlements) of households by electrical appliance ownership and use patterns. These are designed starting from a systematic screening of the literature (Adeoye and Spataru, 2019; Blodgett et al., 2017; Kotikot et al., 2018; Lee et al., 2016b; Monyei et al., 2019; Monyei and Adewumi, 2017; Sprei, 2002; Thom, 2000) about electricity consumption in developing countries and parametrised based on data from recent field visits in Kenya by the authors and their team (2019). The empirical screening provides the rationale to compile tables of appliances and usage patterns (refer to Appendix 2) for each household type. A total number of 22 appliances is selected and modelled across 11 dimensions (ownership, number of appliances per user, appliance power, number of daily functioning windows, windows start and end times, percentage of variability of windows start and end times, daily functioning time, percentual of random variability of daily functioning time, minimum time the appliance is kept on after switch-on event, percentage of occasional use, weekend or weekday use). These dimensions are summarised in Table 1. In order to account for seasonality of the load in the residential sector, the climate variable is taken into account and the months of January and December are considered the hottest in the country, while June and July the cooler. The appliances related with thermohygrometric well-being inside the households, namely fans and air conditioning systems, are modelled according to this climatic variability. In detail June and July are assumed to have no use of such appliances, and the other months gradually increase their use up to a full use in the months of January and December. Given the proximity to the equator of the country, dusk and dawn times are considered to not vary significantly enough to justify seasonal variation of time of use of appliances and lights. The entire set of modelled appliances, users and user types with relative parameters are reported in Supplementary File F3.1.

Table 3.1: Dimensions considered in the stochastic demand assessment. Source: Lombardi et al. (2019).

Dimension	**Description**	**Range**
Ownership	Category of User that owns the appliance	User Type
Number of appliances per user	Number of that specific appliance owned by the user	Non-negative [-]
Appliance power	Nominal power of the specific appliance, allows for a random variability in a defined range for thermal appliances	Non-negative [W]
Number of daily functioning	Number of time “windows” in which the appliance is used during the day	1-3 [-]

windows		
Window start and end times	Hours of start and end of time windows in which the appliance can be used	00:00 – 23:59
% variability of window start and end times	percentage of allowed random variation of the length of the usage windows	0-100 [%]
Daily functioning time	total amount of time that the appliance is used during one day	0-1440 [min]
% of random variability of daily functioning time	percentage of allowed random variation of the total daily time of use	0-100 [%]
minimum time the appliance is kept on after switch-on event	minimum amount of time the appliance stays on after has been switched on	0-1440 [min]
percentage of occasional use	probability that the appliance is used on a single day	0-100 [%]
Weekends or weekdays use	allows to constrain the usage of the appliance only in weekdays or in weekends periods	we / wd / none

Thereafter, the RAMP stochastic demand model (see Figure 3.2) is used to simulate for each of the ten household classes a representative community of *n*=100 households (to ensure sufficient stochasticity). For each cluster i, The RAMP model generates 12 month-specific load curves (in W), at a minute time-step for 365 days, from which it is easy to calculate the total residential power consumption (in kWh).

To parse the simulated energy demand profiles with each population cluster (see Appendix 2), we firstly evaluate the statistical association between the distribution of the population with electricity access across electricity access tiers (based on validated, satellite-derived data on the prevalent tier of electricity access at each pixel (Falchetta et al., 2019) and with reference to the World Bank Multi-Tier Framework for measuring energy access (Bhatia and Angelou, 2015)) and the type of settlement (urban or rural prevalence (A.J. et al., 2019)), the local population density and the distribution of wealth within of sub-Saharan African countries (based on household survey data from the USAID DHS StatsCompiler (USAID, 2009)). Then, based on the regression coefficients we allocate each household without access to electricity enclosed in each cluster to each of the RAMP-generated demand profile archetypes. The process therefore assumes that the distribution among electricity access tiers of those who already today benefit from electric services at home in each cluster will also apply to households that will gain electricity access in the future.

The service infrastructure energy demand is modelled in a similar fashion to the residential assessment, we design baskets of appliances ownership and use for tiers of each category of facility (detailed in Supplementary File F2.2). Scientific (Giday, 2014; Olatomiwa et al., 2018) and grey (Action, 2013) literature on the theme exists, but is often generic and usually scarce when it comes to sub-Saharan Africa. Thanks to a field campaign conducted under the supervision of the authors in primary schools and rural healthcare facilities of Kenya and based on a survey and empirical observation of the appliance ownership and use, energy consumption, and pupils or hospital beds hosted, we are able to reconstruct the field energy demand data in the RAMP model and allocate it to the (latent) demand of clusters where similar facilities are located. Information on operational healthcare facilities is based on open-data on the location and characteristics of public[2] healthcare facilities (Maina et al., 2019). Similarly, open-data for the position and size of schools is retrieved ("Kenya Open Data Initiative - Humanitarian Data Exchange,"

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[2] To date there is no comprehensive publicly available dataset of private healthcare facilities in sub-Saharan Africa.

n.d.). We classify healthcare facilities into five tiers following the criteria presented in the Appendix 2 and the facility type explicated in the original dataset (Maina et al., 2019). Once information about the location and typology of healthcare and education facilities is compiled, we calculate the density of facilities of each tier in each cluster. Based on this information, we estimate the total local sectoral demand exploiting the 1-minute resolution, tier-heterogeneous, monthly-seasonal demand profiles calculated in RAMP. The seasonality of school facilities is indeed dependent on the national school calendar[3], and has been modelled accordingly.

Approximating the residual productive demand from microenterprises (in the context of developing countries defined as small businesses employing few, generally household-related, people and with a limited turnover) is challenging task because of the lack of granular country or region-wide data, which makes it impossible to model at an appliance, plant, or facility level. Proxy estimation approaches have been introduced (Moner-Girona et al., 2019; Parshall et al., 2009). Here (Appendix 2) we propose a model based on employment, infrastructure proximity, and wealth to create a bottom-up residential demand multiplier factor ranging between +30% and + 60% (Moner-Girona et al., 2019). In particular, we carry out a PCA (principal component analysis) to create a composite index based on relevant drivers of productive activities (such as road density, accessibility, employment levels and wealth distribution). The composite index is used to define the local residential demand multiplier factor, which is used to derive the yearly productive demand on top of the residential demand. The baseline load curve (share of demand at each hour of the day over the total daily demand) of micro productive activities is assumed to follow the same path of that described in ref. (Moner-Girona et al., 2019) for Kenya, which in turn is derived on real metered data. A seasonal variation is imposed on the baseline load curve, so that each monthly curve follows the same monthly relative mark-up observed in the residential demand.

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[3] https://publicholidays.co.ke/school-holidays/2020-dates/

3.2.3. Load curves for agricultural productive uses: the relevance of the WEF nexus (Water, Energy, Food security)

Currently in sub-Saharan Africa more than 90% of total cropland is rainfed (Xiong et al., 2017), with the figure standing at about 95% in Kenya (The World Bank, 2019). Together with the lack of fertilisation, the unmet irrigation water demand implies a situation of sub-optimal production, in what has been defined the *yield gap* (GYGA, 2017; Mueller et al., 2012). Moreover, the bulk of the production is either for subsistence purposes or is sold to wholesale markets unprocessed. This is because of the lack of crop processing facilities in most small and medium farm businesses (Sims and Kienzle, 2017, 2016), also because of the lack of energy supply to power those plants, as well as due to market accessibility issues. Most farms thus sell their production to few large processing plants or supply it directly to wholesale markets, where crops are shipped abroad for overseas processing in larger-scale and more efficient plants. The transition from rainfed to artificially irrigated agriculture through surface or groundwater electrical pumping thus provides a relevant example of how an electricity input could dramatically boost rural productivity. Moreover, generating value added through local crop processing (Kyriakarakos et al., 2020) and retaining it among farms would considerably boost local socio-economic prospects, with the potential to set a positive feedback involving the entire local rural community. To enable these uses, the provision of energy is necessary (Barnes and Floor, 1996; Cabraal et al., 2005; Kirubi et al., 2009; Pueyo and Maestre, 2019), along with the purchase of machineries and infrastructure. In fact, currently 85% of the global population without electricity access is concentrated in rural areas (IEA et al., 2020). While planning energy solutions which can comprehensively enable agricultural uses might increase the required power capacity and upfront investment, it might also render them economically attractive because of the significant reduction in the payback time of those investment thanks to the increased rural productivity (Kyriakarakos et al., 2020).

Following this paradigm, here (Figure 3.3) we estimate the energy requirements to enable sufficient artificial irrigation (see Appendix 2 for the detailed methodology) and raw crop processing to more refined crop products, with the final objective of evaluating the potential local economic gains. For irrigation modelling, Agricultural land, hydroclimatic factors, and cropping patterns information is conveyed in a set of agroclimatic equations to estimate daily irrigation water requirements in each cluster. Then, a groundwater pump model estimates the required power and flow rate of the pump as a function of the groundwater dwell characteristics and of the irrigation requirements.

For crop processing energy, an extensive literature review of crop processing energy requirements in the context of developing countries is carried out and associated to crop-specific cropland extent and average yield in each cluster. Finally, the most recent database of wholesale prices for a large basket of crops in Kenya relative the location of each wholesale market is multiplied to the local potential for yield increase of each crop, net of transportation and total (installation, operation, and maintenance) pumping costs.

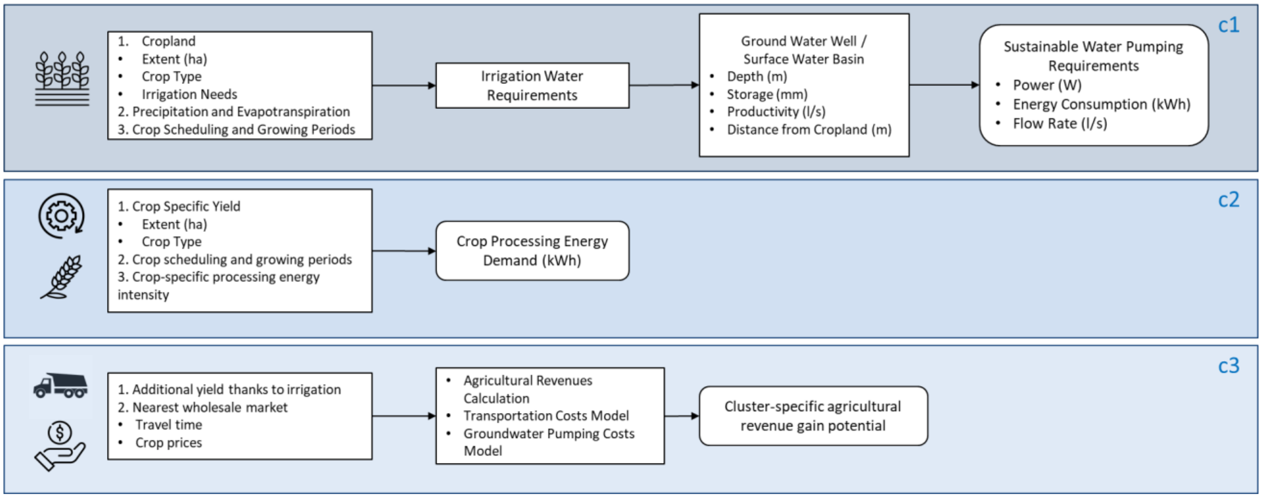


Figure 3.3: Workflow of the agricultural sector in the M-LED framework. (c1) Water pumping electricity requirement estimation procedure. (c2) Crop processing electricity demand estimation. (c3) Agricultural revenues calculation. Source: author’s elaboration.

3.3. Results

3.3.1. An applicative example for Kenya: electricity demand revised

We select Kenya as a country-case study to provide a proof-of-concept of the implementation of the M-LED framework to evaluate sectoral, spatial and temporal energy demand heterogeneity. The selection is the result of two factors. First, data and geospatial information availability in Kenya is remarkable compared to most of SSA countries, which renders the platform implementation comparatively more accurate. Second, a large number of assessments have been carried out on electricity access planning in Kenya (Berggren and Österberg, 2017; Fabini et al., 2014; Moksnes et al., 2017; Moner-Girona et al., 2019; Parshall et al., 2009), and thus there are significant opportunities for better understanding the impacts of our multi-sectoral, bottom-up electricity demand modelling on the outputs of several electrification planning models. On top of it, the lack of available and complete field energy profile data in Kenya offers the opportunity to the M-LED to evaluate and intercompare the significance of the different demand scenarios. A selected list of these studies – all focusing on geospatial electrification analysis for Kenya but applying different tools and assumptions – include refs. (Lee et al., 2016a; Moksnes et al., 2017; Moner-Girona et al., 2019; Parshall et al., 2009).

The panels of Figure 3.4 provide the resulting spatially-explicit (the original results are at a polygonal cluster-dependent resolution; here to ensure a more immediate understanding, they are plotted on a 1x1 km grid) sectoral electricity latent demand generated for Kenya with the M-LED platform. The estimated demand encompasses multiple dimensions: sectoral granularity; monthly seasonality in the demand; hourly profile; and spatial distribution of the demand.

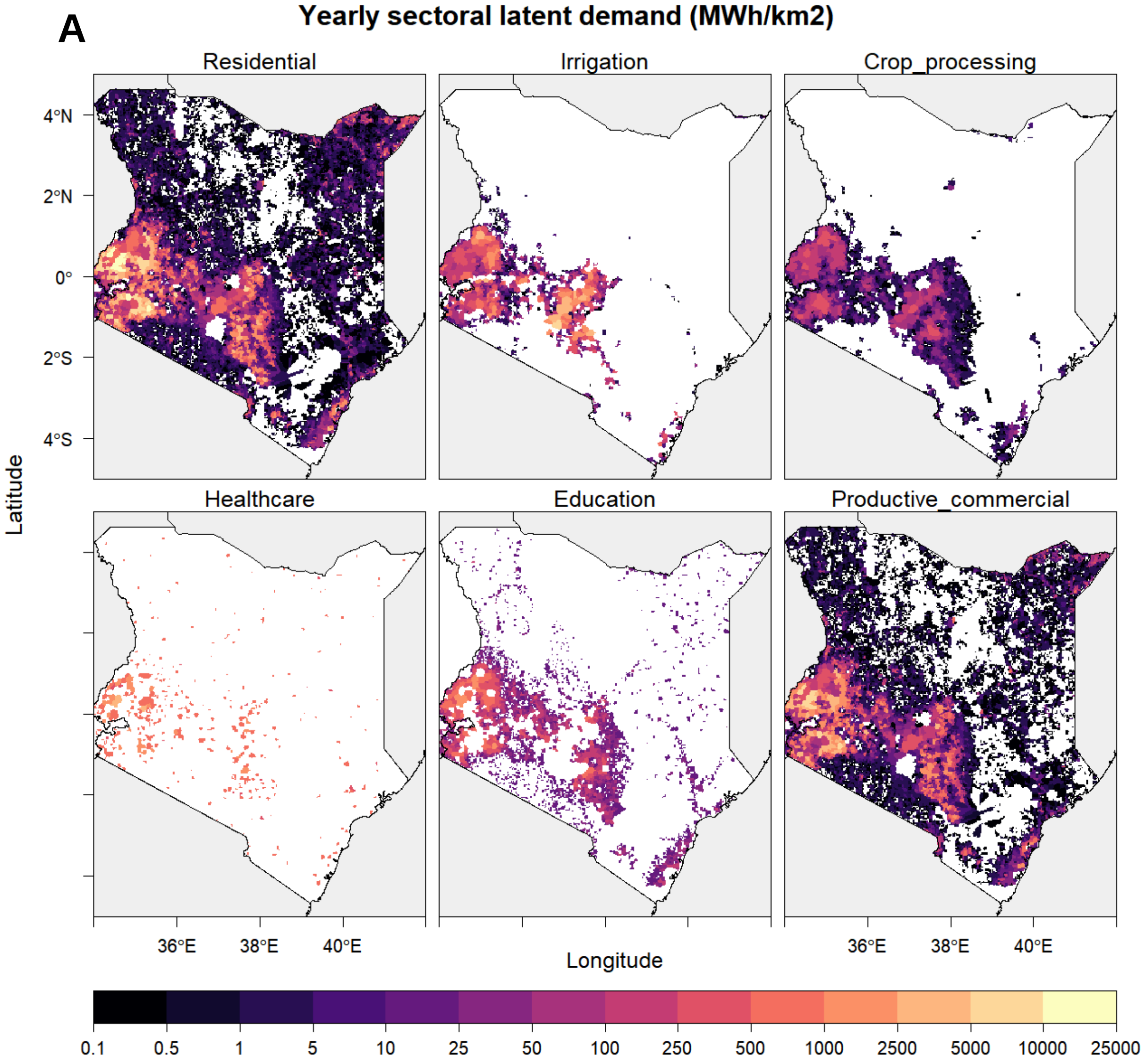


Figure 3.4A shows the distribution over space of yearly sectoral latent electricity demand density (MWh/year/km^2). Note that white pixels identify areas with either no population or no sectoral latent electricity demand, such as natural parks, protected areas, or cropland (for sectors different from agriculture). The results show that substantial heterogeneity is observed in the residential and commercial and micro-enterprise demand: both are highly correlated with population density, with significantly higher latent demand in south-western Kenya. Yet in some areas (e.g. in northern Kenya) commercial and micro-enterprise demand is comparatively lower than the residential demand because of lower employment and market accessibility. Irrigation and crop processing electricity demand are concentrated in the agricultural districts in the south-west of Kenya, while healthcare and education demand are more scattered across the country, although with higher density in higher density populated areas. In particular, healthcare facilities are highly sparse but at the same time exhibit a

high demand density, while schools are relatively more distributed but less electricity intensive.

B

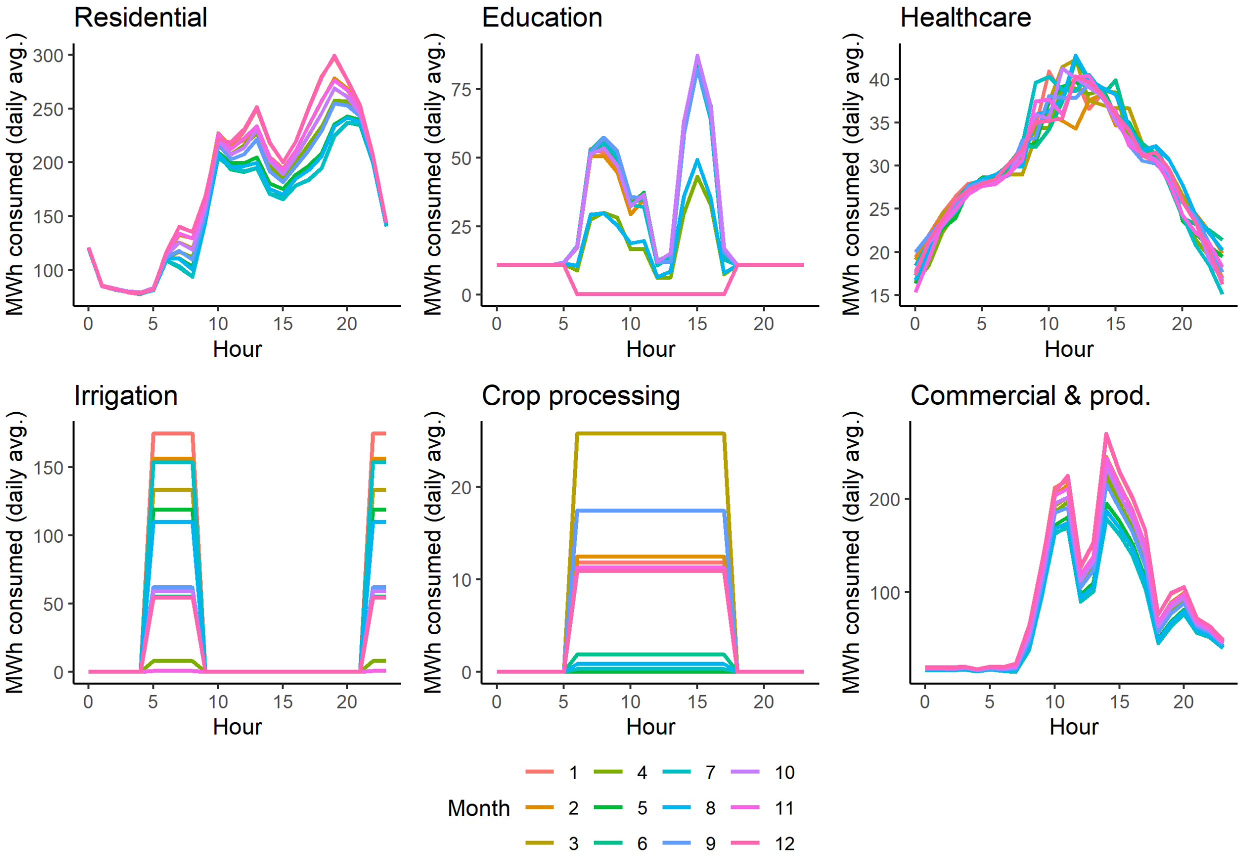


Figure 3.4B depicts the hourly and monthly distribution of the demand across sectors. Residential demand shows a curve with three peaks, during wake-up, lunch, and evening times. A similar polymodal distribution characterises commercial and micro-enterprise demand Most of the seasonality is explained by the variation in the use of air circulation and cooling appliances, since residual uses are rather invariant throughout the year given the proximity of Kenya to the equator. Educational centres show variation in months of year and term breaks with energy demand bimodal distribution with peaks in the morning and in the afternoon. Healthcare results show relatively little seasonal variation, with unimodal normal distribution with a peak at midday for healthcare. Agricultural-related activities show high seasonal variance in the monthly profiles, but the load of the two curves are however flat throughout the energy use windows, 5 am – 9 am and 9 – 11 pm for irrigation and 6 am – 6 pm for crop processing machinery.

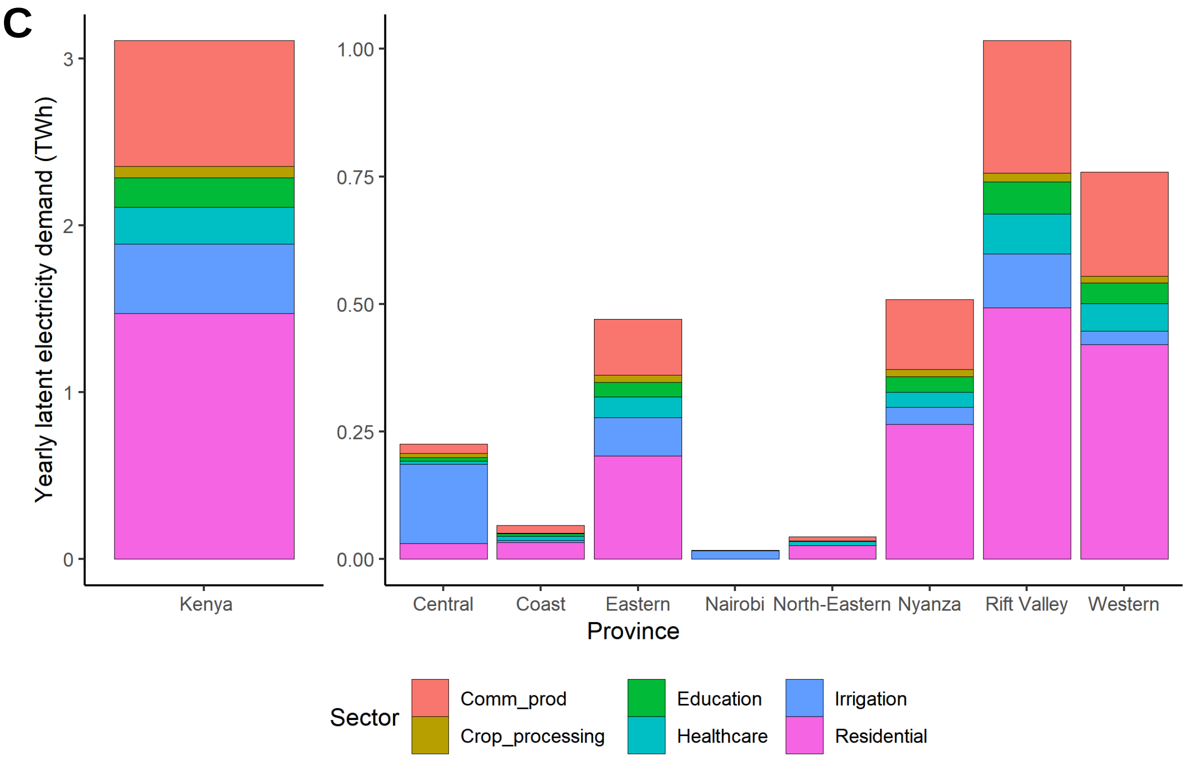


Figure 3.4C summarises the yearly aggregated latent demand across sectors in Kenya and its repartition among the eight regions of (visualised on a map in Figure 3.4D). The country-wide aggregation shows that the supply requirements are unevenly split into the residential (at about 1.5 TWh/year, or 48% of the total 3.1 TWh/year), commercial activities and micro-enterprises (nearly 0.75 TWh/year, about one quarter of the total), healthcare (about 0.22 TWh/year, or 7%), education (0.18 TWh/year, 5.7%), irrigation (0.42 TWh/year, 13.5%), and crop processing sectors (about 0.07 TWh/year, only about 2%). Additional insights are drawn when considering the repartition of those aggregate energy requirements across the eight main regions of Kenya, as well as the shares of each sector within each region. The Rift Valley region is the region with the largest latent demand (about one third of the total latent demand), driven mainly by the residential and productive sectors; it is followed by the Western region (about 25% of the country latent demand), with a similar repartition. Notably, in the Central region irrigation latent energy is by far the first sector (>two thirds of the total).

D

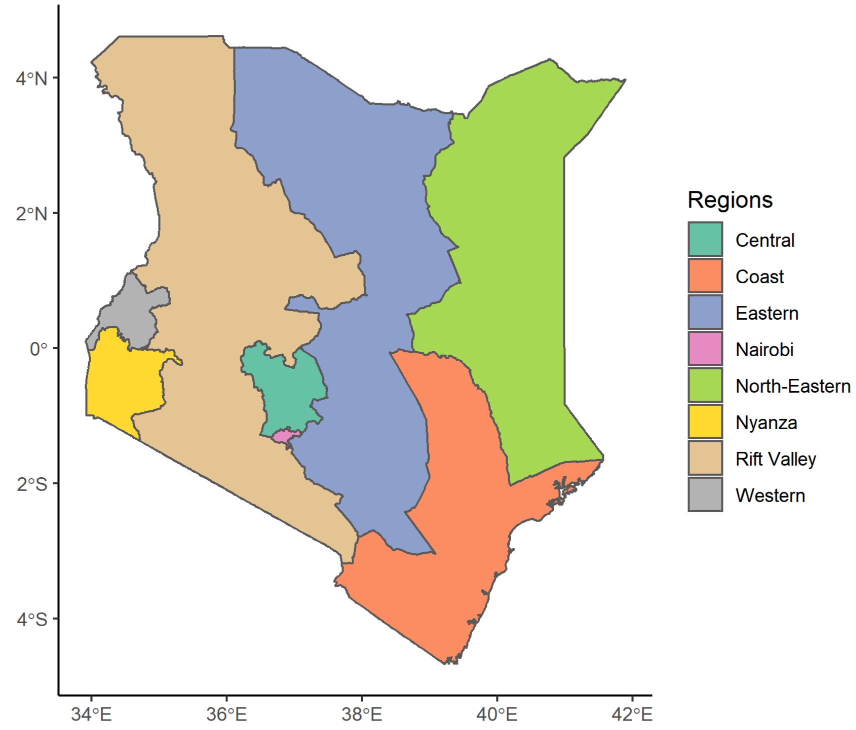


Figure 3.4: Sectoral demand loads in population clusters of Kenya estimated with the M-LED methodology. (A) Maps of Kenya representing: (i) the estimated residential demand density for households that require electrification (MWh/year/km^2); (ii) the total healthcare and education demand density for facilities requiring electrification (MWh/year/km^2); (iii) the water pumping and crop processing demand density (MWh/year/km^2); (iv) the micro-enterprise and commercial activities electricity demand density (MWh/year/km^2); (B) Total (country-wide) typical daily sectoral load profiles, by month (MWh/hour in each demand cluster); (C) Barplots comparing the yearly total regional and country-level sectoral latent electricity demand (TWh/year); (D) Map of the corresponding regions in Kenya. Source: Author's calculations.

3.3.2. **Comparison of the estimated demand with previous studies**

A systematic comparison of our results with previous demand estimates found in the literature (in most cases used to parametrise geospatial supply-side electrification models) is not straightforward. This is because of the differences in both how this demand is formulated (e.g. yearly sectoral consumption in kWh or representative day load curves in W) and how it is parsed to settlements (urban/rural, poor/non-poor). Nonetheless, a number of insights can still be drawn.

For instance, Moksnes et al. (Moksnes et al., 2017) adopt tier-based values of 44 and 423 kWh/capita/year for rural households and of 423 and 599 kWh/capita/year for urban households in the two scenarios they consider. This yields to average demand values of 141 and 468 kWh/capita/year for households to be electrified. Yet, the study considers neither the temporal variability in the demand nor additional demand sectors.

Parshall et al. (Parshall et al., 2009) allocate household demand to a range of 360-1800 kWh/hh/year depending on their urban or rural status and the prevalence of poverty in the region where they are located. Productive demand is fixed across the same categorisation, with values between 50 and 340 kWh/hh/year. This results in an average yearly productive to residential demand ratio of 0.18 Irrespective of the model not encapsulating an explicit temporal dimension of the demand, a peak load is assumed across productive, service, and institutional uses of energy through a peak coincidence factor. The authors assume the following yearly total electric consumption for different facilities: clinic – 360 kWh/year, dispensary – 600 kWh/year, health centre – 2400 kWh/year, primary school (day) – 1200 kWh/year, secondary school – 2400 kWh/year, boarding school – 15,000 kWh/year. Hospitals were not included because they were assumed to already have adequate access to electricity.

Moner-Girona et al. (Moner-Girona et al., 2019) define a different load profile for each energy demand sector. each load profile is the same all year round without seasonal variability but different load peak depending on the location (i.e. number of population) year. In particular, for productive activities small-scale industrial infrastructures with a range of 1500 kWh/year to 3100 kWh/year and commercial activities with a range of 1200 kWh/year to 1800 kWh/year year are considered, while for household demand they follow the approach of (Parshall et al., 2009) to allocate Tier 3 and Tier 4 yearly consumption values, i.e. 365 and 1020 kWh/hh/year.

In the M-LED platform application for Kenya we estimate average urban and rural residential electricity demand of 62 and 842 kWh/hh/year, respectively. Yet, it must be remarked these values do not represent the heterogeneity in the demand that characterised our methodology. The country-wide average yearly productive (commercial and agricultural) to residential demand ratio of our assessment is of about 0.8, while the services (healthcare and education) to residential demand ratio is of 0.25. We calculate average healthcare facility consumption values of 2,200 kWh/year for dispensaries, 10,900 kWh/year for health centres and 124,886 kWh/year for sub-district hospitals. For schools, we estimate a value of about 6,000 kWh/year for a 700 pupils institute.

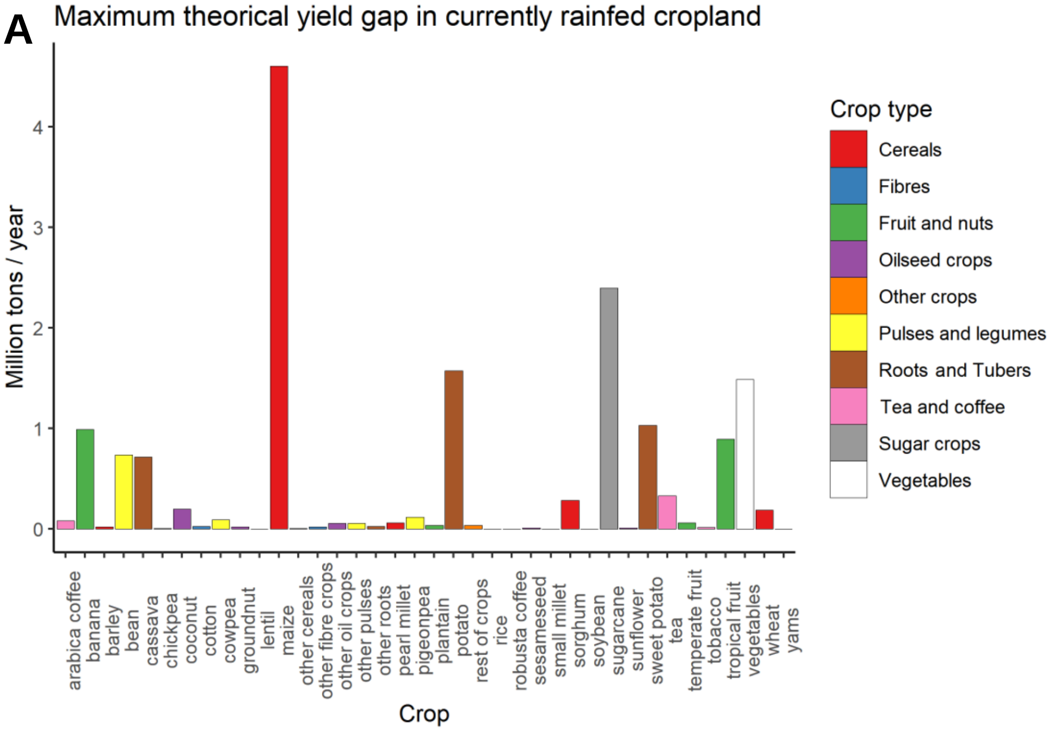
In general, this comparison suggests that the detailed characterisation of our study leads to significant differences with a number of previous studies. Firstly, including productive sectors in our characterisation increases notably both the total load of settlements and the productive-to-residential demand ratio. Secondly, it leads to a larger spread in the residential demand between urban and rural areas. Yet, when encapsulating activities such as artificial irrigation and crop processing, the gap in the demand between settlement types is reduced.

On the other hand, a visual comparison of demand maps suggests that the spatial distribution of demand hotspots is identified similarly through different approaches, provided sectors additional to the residential demand are considered. This is because the key non-residential demand drivers considered in these studies are often similar and highly correlated among each other, such as population density, urban/rural prevalence, poverty density or wealth distribution, and the geographical position of service and productive infrastructure and of crop fields. Yet, studies focussing on achieving universal electrification based on residential demand only flatten the heterogeneity in the demand. For instance, by setting a top-down rural demand they significantly underestimate the demand of rural settlements compared to urban areas;

3.3.3. Impacts of artificial irrigation: increasing local agricultural revenues

The M-LED platform allows the cost-benefit analysis at (partial) local micro-economic level (Appendix 2). The cost-benefit analysis of the increased agricultural yield due to groundwater pumping serves as an applicative example to show one of the many aspects of local development that could be triggered by electrification. The analysis estimates the irrigation needs to close the yield gap by calculating the current yield (in t/ha) of each crop in each agricultural cluster and comparing it with the mean yield of the same type of crop in global areas falling in the same irrigated agro-ecological zone. The workflow then evaluates the potential local economic value added. The potential revenues for local producers are calculated by subtracting transport and total pumping costs to revenues (in turn calculated assuming the wholesale crop price in local markets). It is crucial to remark that these revenues are direct revenues to the producers, so they do not include so does not include export, taxes, and additional cost components. For the Kenyan case study, each crop wholesale price is assumed to be the 2019 price observed at the nearest wholesale market to each functional agricultural cluster (obtained from NFAIS, the National Farmers Information System of Kenya; http://www.nafis.go.ke). The transportation costs of crops from field to wholesale markets are calculated including the fuel consumption, truck rental, and time cost of carrying the extra agricultural production to the market following the shortest path based on recent accessibility maps (Weiss et al., 2018). The pumping costs are calculated estimating a multivariate regression of total pumping costs (including installation, operation, and maintenance components) on the well depth, the pump yield, and their interaction based on real field data from ref. (Xenarios and Pavelic, 2013).

Figure 3.6A shows the maximum theoretical yield gap in current cropland for each specific crop. These aggregated values express the national yield gain potential if cropland was optimally irrigated, fertilised and managed (the latter two components are not modelled in this study). The results show that significant increase in the crop production exists for maize (>6 million tons/year), potatoes (>2 million tons/year), sugarcane (about 2.5 million tons/year), and bananas and fresh vegetables (both at about 2 million tons/year). Yet, the effective profitability of this potential yield gains is a function of several factors: crop prices at wholesale markets, groundwater pumping costs, and transportation distance and time (and thus costs) to these markets. In electrification supply-side analysis, agricultural revenues can be compared to the local electrification investment requirement to assess what would be the payback time of the local electricity access investment if it was covered by the additional agricultural yield generated thanks to electrification itself.



B

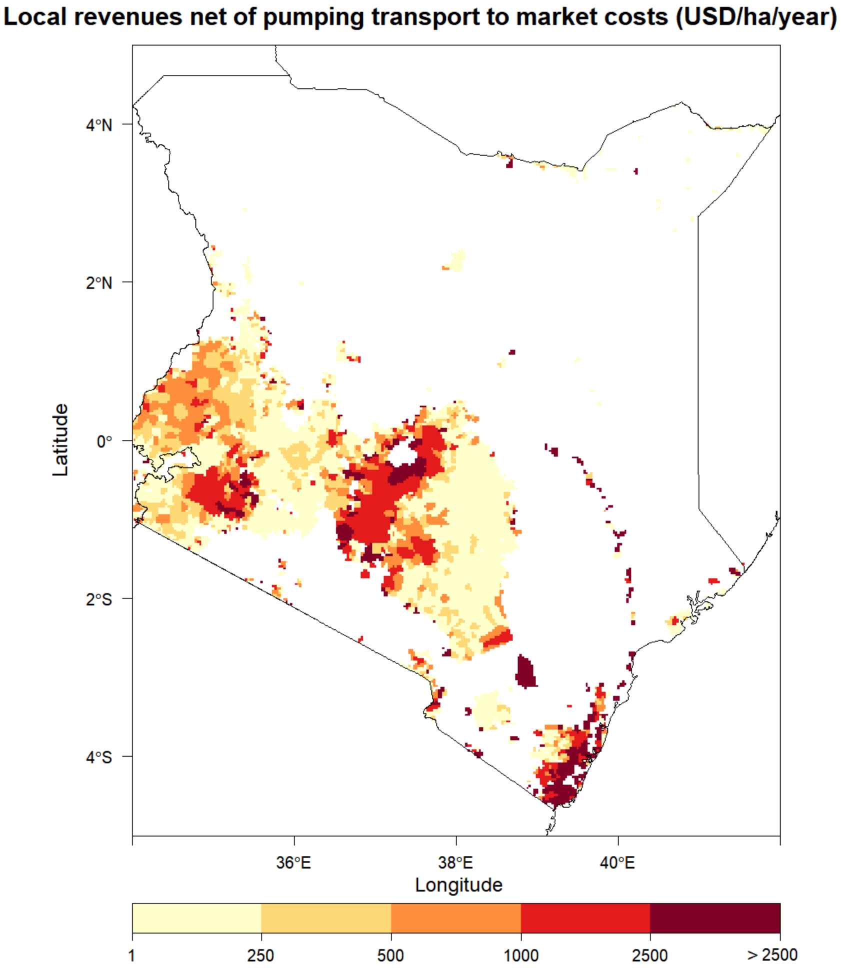


Figure 3.6: Potential revenues from the increased agricultural yield thanks to artificial irrigation. (A) Maximum theoretical yield gap for each deployed crop in Kenya (yield comparison with and without artificial irrigation) (B) Map of Kenya showing the total revenue gain (in USD/ha/year) at current crop-specific market prices including subtraction of field to market transportation costs and groundwater pumping total costs. Source: Author's calculations.

Figure 3.6B summarises the results of the model-based assessment with a map of Kenya plotting the potential revenues (net of transportation and pumping costs) from the increased agricultural yield thanks to artificial irrigation at each cluster. The map shows that in rural Kenya there are vast areas with gain potential of up to 2500 USD/ha (especially in the already comparatively more profitable agricultural district in western Kenya), and even larger areas with more modest but widespread revenue growth potential. These potential gains are very relevant especially if compared to the current income levels of rural Kenya. The proportion of Kenyans living on less than the international poverty line is in fact at 36.1% ("Poverty Incidence in Kenya Declined Significantly, but

Unlikely to be Eradicated by 2030," n.d.). The poverty line is set at 1.90 USD per day in 2011 PPP; thus, assuming an average household size of 3.5 (United Nations, Department of Economic and Social Affairs, Population Division, 2019), as an yearly household income of 2,427 USD. Overall, summing all the potential revenues in the country, a total potential of $4.9 billion/year results, about 5% of the 2019 Kenyan GDP.

3.4. Discussion and conclusions

A detailed formulation of electricity demand is a crucial factor in energy access planning. This is also reflected in the outcome of supply-side electrification models. Here we have introduced M-LED, a flexible platform for generating electricity demand curves based on a multi-sectoral bottom-up device-based approach. We have then applied the platform to the country-study of Kenya.

The analysis provided an array of novel insights, the crucial ones being that modelling electrification based on residential demand only is likely to strongly underestimate the total demand of settlements (and chiefly rural areas), confirming recent assessments in the literature (Moner-Girona et al., 2019). In particular, including healthcare, education, commercial and micro-enterprise, and agricultural energy uses implies (country-wide) a more than doubling of the estimated yearly latent demand vis-à-vis residential only. This mark-up is even greater in agriculture-intensive rural areas where energy uses for irrigation and crop processing might be significant higher in relative terms. Another crucial insight is given by our hourly and seasonal-variant formulation of sectoral load curves, which could have a significant impact on the optimisation of energy systems, in particular when paired with variable renewable energy supply curves.

This paper introduces the demand estimation methodology and results. Yet, future functionalities, currently in the design stage, will link the high-resolution hourly, seasonal, and sectoral demand estimates into an array of electricity supply planning models. The new functionality will allow to carry out an independent assessment for several electrification planning models and understand the significance of considering the new multi-sectoral and seasonal dimensions.

Concerning the specific country-study of Kenya, our analysis reveals that the sectors considered in this study as additional to the residential sector constitute a very relevant share of the total latent demand in areas electricity access deficit. In aggregated terms, they account for ~53% of the yearly latent electricity demand, or 1.65 TWh/year. The ratio between residential and non-residential demand is even more pronounced in the Central region, where although the household electricity access levels are already quite high, agriculture-related activities necessitate significant electricity input which today is largely missing. Additionally, in population-dense areas productive and commercial demand also has a significant impact on the final regional demand.

On top of the detailed latent electricity demand results, the M-LED platform enables an analysis of the potential economic returns from the agricultural sector as a result of the artificial irrigation. This reveals an untapped revenue potential (net of transportation and groundwater pumping costs) of about $4.9 billion/year (about 5% of the 2019 Kenyan GDP). This suggests significant untapped potential that in many areas may quickly pay back the electrification investment if properly accounted by decision makers in the cost-benefit analysis and supported by policies stimulating improved land management and fertilisation. Yet, it must be remarked that additional relevant dimensions that might affect the results of the analysis in the future include the price change of products owing to crop processing and local value creation and the efficiency gains in transport from improved road or rail transportation and logistics.

The M-LED platform is open-source and fully customisable to let the user define the bulk of the technical and economic parameters, the devices ownership and usage patterns, and the overall infrastructure. Irrespective of the large amount of work involved in the development of the M-LED platform and in the formulation of its assumptions, limitations remain. Firstly, a limited number of sectors is estimated; secondly, the data-intensiveness of the analysis implies growing uncertainty over the reliability of the database, as (despite a careful data selection and wrangling) some sources such as infrastructure and facilities location and characteristics might be outdated or biased; thirdly, while the appliance ownership and use baskets are designed after a careful literature screening supported by field campaign experience of the authors, residual cultural, service, and economic heterogeneity might not be captured in the analysis; moreover, in the supply-side analysis a relevant role is played by the techno-economic characterisation of technologies, which might however be affected by future policies such as subsidies and taxes or specific regulatory frameworks; finally, the water and agricultural analysis stands on the assumption of an optimal irrigation scheduling and local crop processing based on current cropping patterns.

Another important aspect concerns the complex dynamics that link the provision of electricity, the potential structural transformation that will follow, e.g. labour market reallocations or the creation of new income generating activities, discussed into depth in Chapter 1.3 of this Dissertation. While the M-LED platform seeks to fulfil certain *a-priori* (i.e. policy driven) defined energy service needs, such as the uptake and use of given appliances in households, hospitals and schools, part of the energy demand as a result of potential structural change is accounted for. In fact, the estimated load profiles for agricultural uses (irrigation and crop processing) and small commercial and other productive uses (expressed as a mark-up on top of the residential demand) are implicitly assuming the resulting energy demand from certain structural changes, such as the mechanisation of agriculture and the uptake of productive activities by households. Nonetheless, established methodologies to estimate energy demand growth (e.g. Stevanato et al., 2020) should be coupled with empirical structural change assessments (Chapter 1.3) to explicitly evaluate these dynamics in frameworks such as the M-LED platform.

Overall, our results are potentially beneficial for policy makers, researchers, consultants, and other stakeholders involved in the electrification planning. For instance, the results could contribute to the prioritisation decisions for the allocation of limited governmental funding by leveraging consumers who are likely to have the greatest impact on increasing economic growth thanks to the provision of electricity to existing productive activities or attracting private investments in the most productive areas.

We encourage further research on the topic and improvements to the state of the M-LED platform introduced at the time of the writing of this paper. A better characterisation of potential industrial demand and a dynamic formulation of demand (with intertemporal growth based on income and other determinants) represent potential first-order improvements.

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4. The role of residential air circulation and cooling demand for electrification planning: implications of climate change over sub-Saharan Africa

4.1. Introduction

About 800 million people (>10% of the global population) live without access to electricity at home (IEA et al., 2020). Energy poverty prevents households from meeting fundamental needs, such as taking actions to autonomously adapt to changing environmental conditions. A major adaptation action concerns indoor thermal discomfort mitigation. In fact, , at different periods in the year, residential buildings are already major drivers of air circulation and cooling (ACC) services demand in large parts of the world. Moreover, anthropogenic climate change is projected to increase the absolute amount of heat in air, land, and water and skew its distribution over space and time. In turn, this will very likely boost the demand for ACC services (De Cian et al., 2019; van Ruijven et al., 2019) and therefore increase the thermal discomfort exposure of energy poor households (Mastrucci et al., 2019; Randazzo et al., 2020). It is estimated that over 1.1 billion people globally face immediate risks from lack of access to cooling (SEforALL, 2018), including almost half a billion people in poor rural areas. On top of that, 2.3 billion people may only be able to less expensive and less efficient cooling devices irrespective of having access to electricity (SEforALL, 2018).

The use of ACC services has multiple socio-economic implications, and especially health benefits, as indoor temperature affects health status (Deschenes, 2014; Tham et al., 2020; Vicedo-Cabrera et al., 2018; White-Newsome et al., 2012), night-time sleep quality (Lan et al., 2017, 2016; Obradovich et al., 2017; Pan et al., 2012), and work productivity (Akimoto et al., 2010; Cui et al., 2011; He et al., 2019; Lorsch and Abdou, 1994; Tanabe et al., 2007; Yu et al., 2019; Zivin and Kahn, 2016). This broad stream of literature agrees upon the fact that ACC services can mitigate large part of the current and future indoor thermal discomfort, which is shown to disproportionately affect the poor and most vulnerable population groups (Biardeau et al., 2020; Byers et al., 2018).

On the other hand, a steeply growing ACC demand has major implications for energy systems, both on the demand and supply side (Ciscar and Dowling, 2014; Khosla et al., 2020). Currently, cooling energy already accounts for nearly 20% of the total electricity used globally in buildings (IEA, 2018). In turn, as highlighted by SEforALL (2018), cooling is responsible for about 10% of global warming and growing rapidly. According to that study, space cooling is also the fastest growing energy service in buildings, with their estimates suggesting that by 2050 the global cooling electricity demand will rise by 66-180%. Crucial factors determining this broad range of uncertainty include the efficiency of technologies adopted and of building materials.

Previous studies have quantified global-warming induced amplification of energy demand in both seminal (Barker et al., 1995; Hekkenberg et al., 2009; Scott et al., 1994; Taseska et al., 2012) and recent (De Cian and Wing, 2019; van Ruijven et al., 2019) applications. Related investment requirements for adaptation (Davide et al., 2019), including thermal comfort (De Cian et al., 2019) and costs (Parkes et al., 2019; Rao et al., 2019), have also been assessed. In particular, a number of contributions have evaluated the residential sector energy demand for heating and air conditioning under different climate change scenarios both globally (Isaac and Van Vuuren, 2009) and with specific attention to developing countries (Mastrucci et al., 2019 ; Wolfram et al., 2012). These assessments have shown that the future climate will be a strong driver of energy demand growth.

In spite of the rich background literature (reviewed in Section 2), the lack of a planning-oriented analysis explicitly linking potential household ACC demand to the large electricity access gap affecting nearly one billion people worldwide, is a research gap to be filled. This issue is at the core of Sustainable Development Goal 7 (SDG 7), the energy-related goal in the UN’s 2030 Agenda (United Nations, 2015). Efficient and effective electricity access infrastructure planning strongly depends on local energy demand targets and projections (Lucas et al., 2017), because the energy demand density over space and time has a major impact on the optimal energy system set-up, including technology, generation capacity, and investment requirements. Therefore, it is crucial to understand to what extent ensuring the possibility to use ACC services at different level of appliances adoption and under different climate futures can affect inclusive electricity access plans. Namely, planning approaches that ensure thermal comfort on top of the baseline household electricity needs. Without accounting for these requirements, electrification programs might leave many households in deprivation even after they get an electricity connection because of an insufficient availability of power for meeting needs such as ACC (e.g. refer to Poblete-Cazenave and Pachauri's, 2019 analysis on latent energy demand and

IEA's, 2017 focus on the appliances compatible with different types of energy access solutions).

Assessing the interplay between ACC needs and electrification planning requires quantifying the thermal discomfort that cannot be met because of the lack of electricity access and how the situation may exacerbate over time due to anthropogenic climate change. In turn, this necessitates an integrated understanding of the spatial distribution of populations living in energy poverty, of the variability of ACC needs across space and time, and of a modelling approach to estimate local electricity requirements. To address these questions, we build on the methods introduced in studies examining the linkages between temperature, climate change, income, air conditioning ownership and use – and therefore the future potential electricity consumption. We calculate spatially-explicit monthly cooling degree days (CDDs) – a reference metric for space cooling needs (CIBSE, 2006; Heating et al., 2009) –, for both the present and the post-SDGs horizon (2041–2060) based on Coupled Model Intercomparison Project – Phase 6 (CMIP6) climate simulations (Eyring et al., 2016) – a consortium of Global Climate Models (GCMs) underlying the reports of the Intergovernmental Panel on Climate Change (IPCC). Building on the estimated ACC needs, we develop and implement a spatially explicit framework to estimate the electricity requirements (on top of archetypical baseline demand targets) for a variety of scenarios of appliance adoption, efficiency, and use to guarantee thermal comfort in settlements currently without access to electricity. The assessment encapsulates assumptions on building and appliance characteristics and geo-referenced climate, solar irradiance, human settlement, and survey-based wealth distribution data. These steps culminate in the calibration of a geospatial electrification model for sub-Saharan Africa – the global hotspot of energy poverty – to evaluate the role of ACC for an electrification strategy inclusive of adaptation by 2030, the SDG 7 target year. Namely, we identify universal electricity access scenarios suitable for accommodating current and future indoor cooling needs. The analysis seeks to improve the understanding of the role of climate change adaptation actions in policies targeting the elimination of energy poverty. Particular attention is devoted on the potential of decentralised energy access systems – identified by several sources (Dagnachew et al., 2017; IEA, 2019a) as a fundamental contributor to closing the energy access gap – to enable ACC services use.

4.2. Literature review

4.2.1. Energy poverty: definition, measurement, and implications

Energy poverty does not have a unique definition, because a universally valid understanding of what it means to live below the energy poverty line is missing (Culver, 2017; Pachauri, 2011). In fact, the definition of energy poverty depends on the socio-economic, cultural, and environmental factors at stake at each context. Moreover, energy poverty is not a prerogative of low-income countries: for instance the *EU Energy Poverty Observatory* measures the share of income spent by households on energy bills and by the inability to keep thermal comfort at home in EU countries, finding major issues in different countries where income inequality is also prevalent (Thomson and Bouzarovski, 2018). Yet, seminal inquiries into its definition in high-income regions, such as the UK Government's *Fuel Poverty Review* (Hills, 2011) or Thomson et al. (2016)'s evaluation of fuel poverty in the EU simply cannot be applied to the context of low-income, developing regions. While some similarities can be traced, such as the fundamental economic nature of the problem, stark differences exist. In the developing world, nearly 800 billion people live without access to electricity and 2.8 billion lack access to clean cooking (IEA et al., 2020)**.** In these areas the lack of infrastructure is the primary cause of energy poverty, while high prices of modern energy services relative to income levels are also important.

The lack of a unique, unambiguous definition of energy poverty directly affects the capacity to measure it: energy poverty can be evaluated in terms of energy access, energy inputs (e.g. energy consumed or income spent on energy), outcomes (e.g. adverse socio-economic impacts), and the quality of energy delivered (Culver, 2017). In our paper we pay explicit attention to the concept of energy poverty in the context of developing countries, namely to questions of electricity access, latent energy services demand (Poblete-Cazenave and Pachauri, 2019), and energy access infrastructure planning.

Recent contributions have examined energy poverty measurement in the context of developing countries to overcome mono-dimensional evaluations and allow for a more comprehensive understanding of the challenges involved (Pelz et al., 2018). For instance, the IEA developed the Energy Development Index (EDI) by calculating an evenly weighted average of three normalized components: (i) per capita commercial energy consumption; (ii) the share of commercial energy in total final energy use; and (iii) the electrification rate. The EDI was criticised by Nussbaumer et al. (2012) because it neglects household energy deprivation. The authors introduced the Multidimensional Energy Poverty Index (MEPI), which focuses on household energy poverty only. The Energy Poverty Index (EPI) (Mirza and Szirmai, 2010) pays strong attention to the issue of opportunity costs as a consequence of energy poverty. In a seminal contribution, Bhatia and Angelou (2015) introduced the World Bank Multi-Tier Framework, a matrix for measuring and planning energy access across different dimensions such as availability, affordability, reliability and consumption. Samarakoon (2019) built on this literature to create another framework with focus on the justice and wellbeing aspects, crucial to eliminating energy poverty. A recent update of the debate on advancing energy poverty measurement for SDG 7 is offered by Pachauri and Rao (2020), who criticise the complex nature of most multi-dimensional energy poverty measures, and in response propose an alternative framework based on energy supply conditions and the status of household energy poverty.

The implications of energy poverty for livelihoods and wellbeing are huge, both in developing countries and in high-income regions. In the global south pervasive energy poverty and lack of energy access determine detrimental outcomes for development prospects, public health, gender empowerment, education, and the degradation of the natural environment (Sovacool, 2012). A discussion paper by Casillas and Kammen (2010) highlighted the crucial nexus linking energy poverty and climate change. Thermal comfort and indoor air cooling – at the core of the analysis presented in this paper – fall under the umbrella of the implications of energy poverty (and the lack of electricity access infrastructure) in developing countries and elsewhere. For instance, empirical evidence suggests that wellbeing is strongly affected among those living in fuel poverty: analysing data from Australia, Churchill et al. (2020) found that fuel poverty lowers subjective wellbeing substantially, which large social shadow costs. A similar result was observed by Biermann (2016) in Germany, who highlighted that the impact found is beyond the effect of mere income poverty. Finally, analysing 32 European countries, Thomson et al. (2017) found a higher incidence of poor health (both physical and mental) amongst the energy poor populations of most countries, compared to non-energy poor households

4.2.2. **Energy needs for climate change adaptation, ACC demand, and related greenhouse gas emissions**

The expanded energy demand (including from the growing need for ACC) as a mean to adapt to climate change has been analysed by an at least two decade-long literature. Early studies came from governmental reports in Germany and in the United States that quantified – on aggregate building stock terms – moderate decreases in heating energy and similar increases in cooling energy. An important advancement was introduced in the work by Scott et al. (1994), who evaluated the effects of climate change on commercial building energy demand and discussed the importance of considering disaggregated data in impact assessment studies. They highlight that increased humidity could be a significant factor in total building energy use.

More recent studies include the work by Hekkenberg et al. (2009), who highlight the importance of socio-economic dynamics in mediating the energy demand response to changes in the outdoor temperature. Ciscar and Dowling (2014) carried out a systematic review of how integrated assessment models (IAMs) have estimated the impacts of climate in the energy sector, including the modelling of adaptation. They argue that modelling possible adaptation measures and assessing the effects of climate extremes on the energy infrastructure are topics that require further attention. Another relevant contribution is offered by van Ruijven et al. (2019), who build on empirically estimated responses of energy use to income and hot and cold days globally and project – for an array of scenarios – very substantial increases in global climate-exposed energy demand before adaptation on top of baseline energy demand growth. Similar results are found in De Cian and Wing (2019).

Specific focus on the impact of future air conditioning adoption and use is found in the work of Davis and Gertler (2015), who used high-quality micro-data from Mexico to describe the relationship between temperature, income, and air conditioning. Based on the estimated empirical model – where income is found to be the main driver of ACC systems adoption – they projected the future energy demand growth. The authors concluded highlighting the important role of energy efficiency and of cooling technologies. Isaac and van Vuuren (2009) carried out a global integrated assessment modelling study of residential sector energy demand for heating and air conditioning in the context of climate change. They project income growth to be the key driver of energy demand for air conditioning throughout the 21st century. The authors assume availability of air conditioners as a function of income following a logistic function, with a threshold point beyond which ownership increases rapidly. They estimate the function using data over economic development and appliance adoption from different countries utilizing McNeil and Letschert (2008). Isaac and van Vuuren (2009) then define yearly household electricity consumption from air conditioning as a function of CDDs and the natural logarithm of income and they estimate the equation parameters based on consumption data from the literature. Another contribution comes from Gupta (2012), who estimates the climate sensitivity of electricity demand in Delhi using daily data on electricity demand and apparent temperature through a semi-parametric variable coefficient model. The author finds a electricity demand is a U-shaped function of temperature, with a steeper slope in the rising part growing over the years analysed, implying an increase in cooling demand per unit increase in hot months.

Mastrucci et al. (2019) estimated the current location and extent of populations potentially exposed to heat stress in the Global South applying a variable degree days method to estimate the energy demand required to meet these cooling needs. They account for spatially explicit climate, housing types, access to electricity and air conditioning ownership and find that covering the estimated cooling gap entails a median energy demand growth of 14% of current global residential electricity consumption. Similarly, Parkes et al. (2019) utilize the *apparent temperature* and *humidex* metrics to calculate current and future heat stress in Africa. They find that climate change is projected to increase the intensity of heat stress events in Sahelian Africa and introduce new heat stress events in Northern and Central Africa, with consequent increase in energy-intensive cooling. As the intensity of heat stress increases, they project that energy-intensive cooling will increase, with the most affected country being Nigeria. They estimate the total increase in energy costs to prevent heat stress in Africa at $51bn by 2035 and $487bn by 2076. Finally, the authors highlight the issue of supplying this cooling energy demand in poor countries with low electrification rates, a topic at the core of our paper.

De Cian et al. (2019) analysed household survey data across eight temperate industrialized countries to explore how households have been adopting air conditioning and thermal insulation to cope with different climatic conditions (also through their interaction with socio-economic and demographic characteristics). Their findings stress the crucial role of income and urbanisation in ACC uptake and adoption. Examining the same primary data and countries, Randazzo et al. (2020) evaluated household air conditioning adoption and use patterns. The authors find that households on average spend 35%–42% more on electricity when they adopt air conditioning. They predict adverse impacts of climate change on energy poverty through this dynamic, with increasing population shares spending significant proportions of their income on electricity for ACC purposes. Finally, Colelli and De Cian (2020) carried out a systematic review of the methodologies adopted in IAMs to estimate cooling demand for thermal adaptation in commercial and residential buildings. They highlight that models lacking extensive margin adjustments (i.e. long-term demand responses driven by an increase in the penetration of ACC appliances) systematically underestimate the additional cooling needs of the building sector. They suggest future research to look more in detail into ACC appliances adoption modelling.

Global modelling exercises carried out by the IEA (2019b, 2018) have estimated that by 2050 the global cooling electricity demand will rise by 66-180%, with the global air conditioner stock reaching about 5.5 billion units from the current ~2 billion. The IEA argues that efficient cooling technology and building materials use scenario would imply an ACC electricity demand about half compared to a Reference Scenario, and one third less power generation investment (about \$3-\$2tn globally, respectively). To conclude, Laine et al. (2019) evaluated the potential of the increased electricity demand from growing AC adoption and use to boost solar PV capacity expansion, in particular because areas of high cooling requirements tend to coincide with areas of high PV generation potential. They argue that a majority of the rapidly increasing cooling demand could be met with PV and small-scale distributed storage.

Building on this rich literature background, our study is unique in its kind as it explicitly draws the line between poverty, climate change, future ACC energy demand and electricity access planning.

4.3. Materials and methods

4.3.1. General framework

Figure 4.1 summarises the analysis carried out in this paper. The methodology is divided into four main parts, also highlighted in dedicated sections below:

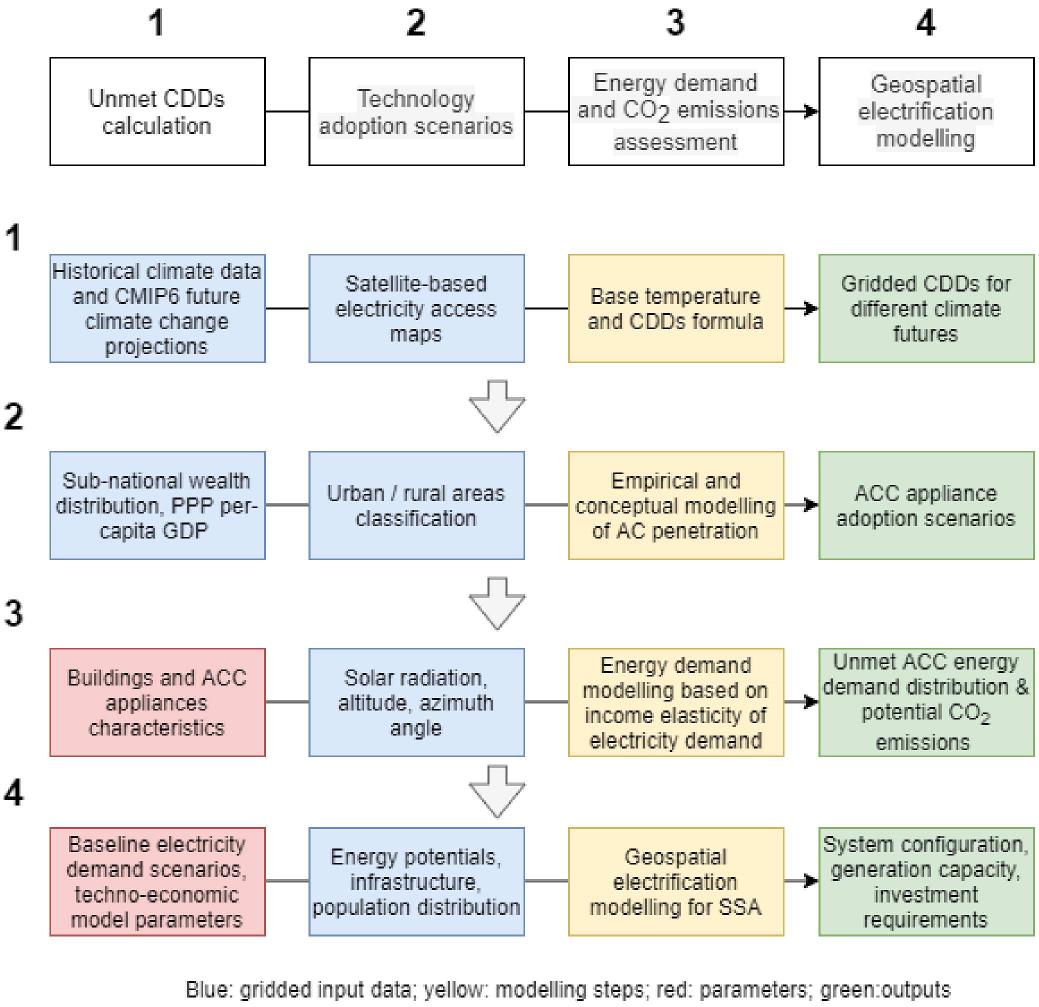


Figure 4.1 **|** *Methodological framework of the analysis.* ***(1)*** *General workflow;* ***(2)*** *CDDs calculation;* ***(3)*** *Electricity demand estimation;* ***(4)*** *Electrification modelling.*

1. Calculation of cooling degree days (CDDs) based on both historical data and future climate change projections; assessment of the distribution of CDDs among households without electricity access;
2. Empirical modelling to define ACC appliances adoption based on household wealth and its evolution and urban/rural prevalence; design of additional appliance adoption scenarios to appraise potential ACC policy objectives;
3. Energy demand modelling to estimate potential ACC-driven energy consumption among households without electricity access under different scenarios;
4. Geospatial electrification modelling to evaluate the role of potential ACC energy demand in electricity access infrastructure planning; results on

system configuration, power generation capacity requirements, and investment needs.

4.3.2. **Cooling degree days: data and calculation**

We calculate the average monthly CDDs – defined as the degrees that the average day of each month's temperature is above an arbitrarily defined comfort temperature (T_{base}) – at each 0.5° grid cell. To derive CDD from average monthly minimum, mean, and maximum temperature values, we implement the CDD methodology developed by the UK Met Office (Spinoni et al., 2018), which is reported in Table 4.1. The methodology represents a step forward from the traditional CDD calculation as the difference between the daily or monthly mean temperature and T_{base}, because it explicitly accounts for the temporal distribution of heat during the average day of a given month. The main limitation of the methodology is that it does not directly account for humidity, which can alter the amount and perception of heat in the air. Yet, humidity is considered in the sensitivity analysis where we use wet-bulb temperature CDDs (Appendix D). These are not used as the reference variable because relevant data is still lacking for the latest CMIP6 climate projections.

Table 4.1: *CDDs calculation methodology*

Condition	**CDDs**
$T_{max} \leq T_{base}$	$CDD = 0$
$T_{avg} \leq T_{base} < T_{max}$	$CDD = \frac{(T_{max} - T_{base})}{4}$
$T_{min} \leq T_{base} < T_{avg}$	$CDD = [\frac{(T_{max} - T_{base})}{2} - \frac{(T_{base} - T_{min})}{4}]$
$T_{min} \geq T_{base}$	$CDD = T_{avg} - T_{base}$

In the analysis, a base temperature (T_{base}) of 26° C is considered. While most global assessments use a T_{base} of 18.3° C, we calculate CDDs at a base of 26° C because the electricity access deficit is concentrated in areas with tropical and equatorial climates where the mean yearly temperature is significantly higher than the global mean temperature. This base temperature is also adopted in the literature on cooling needs in the Global South (Mastrucci et al., 2019). T_{base} values of 22°, 24° and 28° are also utilized for examining the sensitivity of the results to the choice of comfort temperature (T_{base}) following Dongmei et al. (2013).

CDDs are calculated on both historical and projected future climate data for the 2041–2060 horizon. The calculation of historical CDDs is based on 1970-2000 monthly average data from WorldClim (Fick and Hijmans, 2017), while future (potential) CDDs are projected based on the median of CMIP6 downscaled, bias-corrected climate change simulations produced from eight GCMs (*BCC-CSM2-MR, CNRM-CM6-1, CNRM-ESM2-1, CanESM5, IPSL-CM6A-LR, MIROC-ES2L, MIROC6, MRI-ESM2-0*) for the period 2041–2060. For the future climate change, we refer to the CMIP6 scenarios SSP245 (the update of RCP2.6 based on SSP1) and SSP370 (the update of RCP4.5 based on SSP2) scenarios. These integrated scenarios describe interactions between global socio-economic development pathways, namely the Shared Socio-Economic Pathways (SSPs), namely the drivers of greenhouse gas (GHG) emissions from anthropogenic activities, and the Representative Concentration Pathways (RCPs), i.e. the resulting GHGs concentrations in the atmosphere. The logic and construction of SSP-RCP integrated scenarios are described in detail in O'Neill et al. (2016). Scenarios SSP245 and SSP370 represent intermediate emission variants that assume sustainability-focused and middle-of-the road socio-economic trajectories, respectively. SSP245 is more likely than not to result in global mean temperature rise between 2-3° C by 2100, while SSP370 represents the medium-to-high end of the range of future emissions and warming, and it is a baseline outcome rather than a mitigation target (Pachauri et al., 2014).

4.3.3. **Electricity access deficit and CDDs allocation**

First, the spatial distribution of populations currently living without access to electricity is approximated based on the methodology described in Falchetta et al. (2019). The approach combines the 2019 NOAA Suomi NPP-VIIRS (*National Oceanic and Atmospheric Administration, Suomi National Polar-orbiting Partnership satellite, Visible Infrared Imaging Radiometer Suite sensor*) night-time light imagery (as a proxy of electricity access infrastructure proximity) – calculated as the median raster of monthly composites (with a 0.3 $\mu W \cdot cm^{-2} \cdot sr^{-1}$ noise threshold), and the WorldPop 100 m resolution gridded population dataset (Tatem, 2017). The approach estimates populations living in areas that are dark at night, and thus considered without reliable electricity access. The estimation methodology produces a global total of ~880 million people without access to electricity, which is quite consistent with recent assessments of global electricity access deficit (IEA et al., 2020). As discussed in Falchetta et al. (2019) this estimate is highly correlated with field measured electricity access levels at both national and sub-national levels. Note that in the electrification modelling exercise, the population is then projected to 2030 with heterogeneous urban-rural population growth based on UN-DESA (2018) projections.

Then, we estimate *potential ACC demand* (*PACC*), defined as the CDDs that cannot be mitigated at time *t* because of the lack of electricity access, but which would drive energy consumption if households had both an electricity connection and an ACC appliance available. We calculate PACC at each grid cell *i* as a weighted sum:

$$PACC_i = \sum_{t}^{T=12} \frac{POP_{it}^{noacc}}{HHsize_i} \times CDD_{it}$$

(Eq. 4.1)

where:

- POP^{noacc} is the population without electricity access estimated with nighttime light data;
- $HHsize_i$ is the local average household size (calculated at each grid cell using UN-DESA, Population Division (2019) data on country-level average household size and a urban-rural adjustment factor);
- *CDDs* are the local cooling degree days (*CDDs*) for each month of the year *t* for both the present and future climate change scenarios.

4.3.4. ACC technology adoption

4.3.4.1. Empirical modelling of AC penetration

AC penetration occurs mostly at the extensive margin, i.e. in response to changing income and climate conditions (Colelli and De Cian, 2020; IEA, 2020), while also urbanisation is shown to play a significant role (De Cian et al. 2019). In particular, following seminal empirical two-stage model of AC adoption based on country-level analysis worldwide (Isaac and van Vuuren, 2009; McNeil and Letschert, 2008), we define AC penetration P_i^{AC} as:

$$P_i^{AC} = AV_i \times CMS_i$$

(Eq. 4.2)

where AV_i is *availability* (a function linking income and the potential to purchase AC units), defined through the following empirical logistic function (from Isaac and van Vuuren, 2009):

$$AV_i = \frac{1}{1 + e^{4.152} \times e^{\left(-0.237 \times \frac{PPPGDP_i^{2030}}{1000}\right)}}$$

(Eq. 4.3)

where:

- $PPPGDP_i^{2030}$ is the purchase-power-parity per-capita GDP in year 2030 in 1995 US Dollars at grid cell *i*
- *e* is the exponential function
- CMS_i the climatic maximum saturation (a function linking local CDDs with the probability of purchasing AC units), defined from McNeil and Letschert (2008).

In turn, CMS_i (also from Isaac and van Vuuren, 2009) is defined as:

$$CMS_i = 1 - 0.949 \times e^{(-0.00187 \times CDD_i^{yearly})}$$

(Eq. 4.4)

where:

- CDD_i^{yearly} are the cumulative CDD experienced each year at each grid cell *i.*

Since our analysis looks at future adoption and use of AC, we estimate future sub-national income level change with respect to the present. Here, future PPP per-capita GDP at year 2050 ($PPPGDP_i^{2050}$) at each grid cell *i* is calculated as:

$$PPPGDP_i^{2050} = \sum_{k}^{K=5} WQ_k^{DHS} \times \left(1 + HGR_k^{DHS}\right)^{30} \times PPPGDP_k^{2020} \times (1 + HGR_c^{WB})^{30}$$

(Eq. 4.5)

where:

- WQ_k^{DHS} is the share of the population in each wealth quintile *k* according to the latest available DHS survey. Wealth distribution, expressing the share of households in each wealth quintile compared to the national distribution, is a proxy for household income.
- $HGR_k^{DHS}$is the assumed yearly average rate of change in the share of people living in wealth quintile *k*. It is used to (linearly) project future wealth distribution. It is calculated based on the historical evolution of the distribution of wealth at sub-national scale from DHS surveys. Virtually all

provinces have been surveyed more than one time in the last twenty years, so we can calculate the average historical shift in the distribution of wealth (based on the number of years between the different survey waves).

- $PPPGDP_k^{2020}$ is each country's PPP per-capita GDP in year 2020.
- HGR_c^{WB} is the average per-capita PPP GDP growth rate for the 2020-2050 period based on the SSP2 projections (Riahi et al., 2017).

In the calculation, we assume that the $PPPGDP_k^{2020}$ approximates the average income level of people in the third wealth quintile (50% richest share of the population), and therefrom we derive PPP per-capita GDP at other wealth quintiles for both the present and the future. Conversion to 1995 PPP constant USD of current GDP is carried out with the World Bank GDP deflator (indicator *NY.GDP.DEFL.ZS).* Moreover, since DHS surveys are urban-rural stratified, the AC penetration assessment is inclusive of urban-rural heterogeneity.

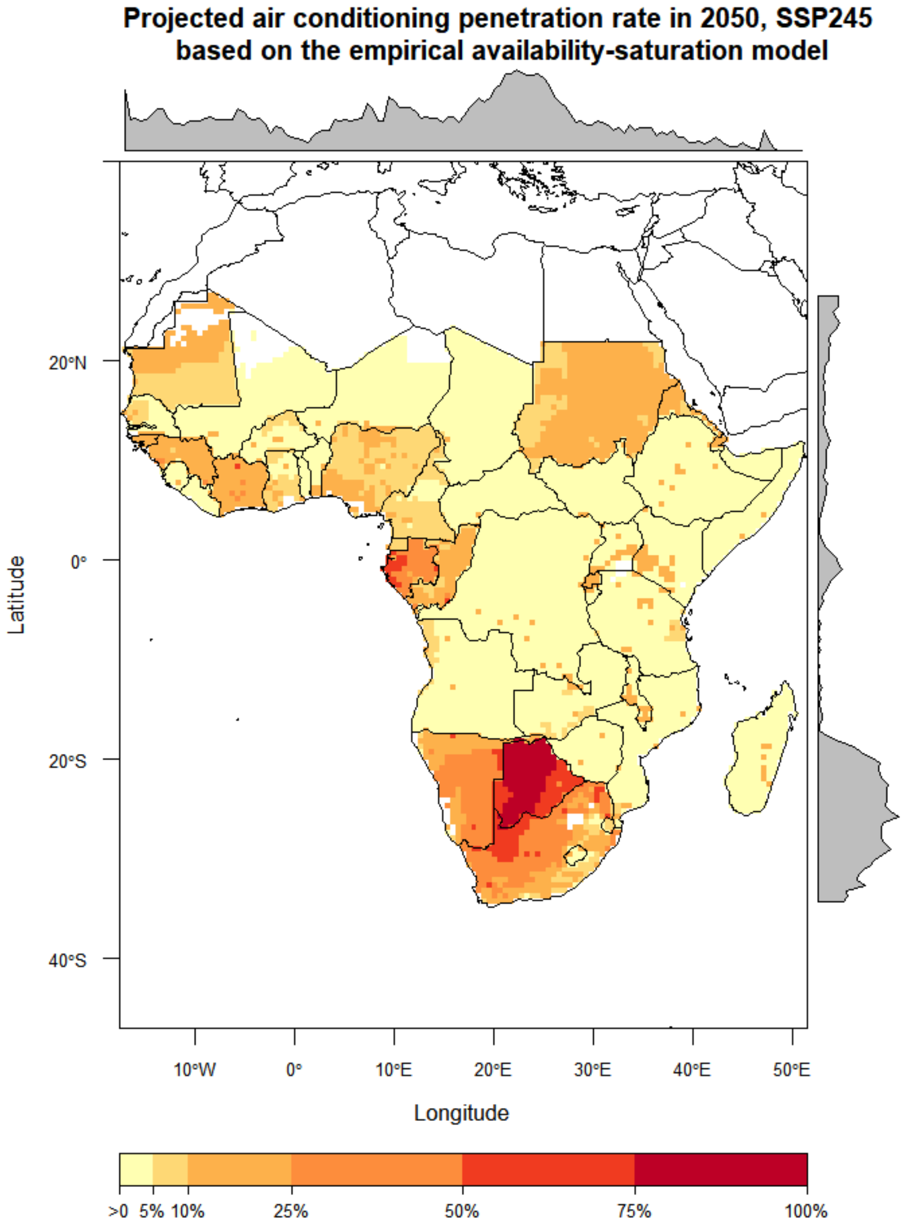


Figure 4.2 | Map of the modelled air conditioning penetration rates in 2050 in the empirical appliance adoption scenario for SSP2-45.

Figure 4.2 plots the estimated AC penetration rate around year 2050 at the pixel level for SSP2. The results show significant variability, with southern and western African countries achieving significant AC penetration, while in broad areas of central and eastern Africa, with the exception the main urban centres, AC penetration remains below 5% even after 2050. These results are consistent with the modelling results of country-level AC ownership in 2050 carried out in IEA (2020), with most SSA countries still showing generally low levels of AC adoption. Alternative estimates under other SSP scenarios can be found in Figure B.3 in the Appendix.

4.3.4.2. Representative ACC technology adoption scenarios

In the empirical AC penetration modelling, large shares of rural populations remain without AC. Yet, given the possibility that the historical relationship between income, climate and AC adoption considered in the assessment will not hold in the future or in the context of SSA, we also simulate two representative scenarios of ACC appliances adoption. These scenarios can be thought of as archetypical policy objectives where more people are able to mitigate the CDDs they experience. In these representative scenarios, we consider separate adoption rates for rural and urban households (HHs) and we link them to the most recent provincial wealth distribution across households from DHS surveys. Urban and rural areas are identified based on the GHS-SMOD 2015 settlements classification to classify populations grid cells either as urban (GHS-SMOD≥30), or as rural (11≤ GHS-SMOD≤23), or as not inhabited (GHS-POP=0) (see Pesaresi et al., 2015 for classification details). We then refer to the United Nations' statistics on the average household size in urban and rural areas of each country (United Nations, Department of Economic and Social Affairs, Population Division, 2019) to define the number of households in each rural and urban cell of each country.

Based on this information, we design two representative technology adoption scenarios additional to the empirical scenario (named S0):

- S1 (*lower AC penetration*): the 80% wealthier urban HHs use AC, the 20% wealthier rural HHs use AC; the remaining HHs use fans;
- S2 (*higher AC penetration*): 100% of urban HHs use AC; the 50% wealthier rural HHs use AC; the remaining HHs remaining use fans;

How can these significantly more ambitious targets than estimated from the empirical AC penetration modelling based on historical global trends be framed? Currently total AC penetration rates in some rapidly developing countries with a warm climate, such as Mexico, Brazil, and Indonesia, stands between 10-20%. But in China they reach 60%, irrespective of similar PPP per-capita GDP levels to those countries, highlighting the crucial role of policy. According to Goldstein Market Intelligence (2020), air conditioner stocks will reach 1.5 billion units in Africa by 2030, more than doubling the stock in 2015. For instance, in Nigeria, more than half a million air conditioning units are bought each year and the number is increasing by 4-5% annually (SEforALL, 2018). Recent reports (Anderson et al., 2020) discuss how upcoming cost-effective and efficient units might boost the policy support for AC.

In the analysis, this appliance adoption classification is relative to HHs facing unmet CDDs, i.e. currently lacking electricity access. Consistently with the literature, even in these scenarios adoption is conditional on the geographical distribution of wealth and on the urban or rural status of HHs (Davis and Gertler, 2015; Isaac and van Vuuren, 2009) and electricity consumption in recently electrified areas (Lenz et al., 2017; Taneja, 2018).

4.3.5. **ACC electricity demand assessment**

4.3.5.1. Air cooling (air conditioning)

Once AC adoption is modelled, we estimate electricity consumption at each location. ACC electricity requirements are firstly modelled technically, namely as the physical energy that would be required to mitigate all the CDDs at each location. As a second step, demand is modelled economically, i.e. as function of the expected income growth at each location and of the electricity demand response based on literature-derived empirical estimates of the income elasticity of electricity demand. The technical modelling of the AC demand is described in detail in Appendix A. This section focuses on the energy-economic modelling.

Since we are analysing households currently without electricity access and thus with no energy consumption, we modulate the effect of income on future AC use. We assume baseline consumption at the representative values of WB-MTF Tiers 2-3 and 3-4 in urban and rural areas, respectively (depending on the scenario considered and to match the baseline electricity consumption values considered in the geospatial electrification analysis; see Section 4.3.7) to estimate the future electricity consumption ($ELCONS_{2030}^{projected}$). The projection is based on empirical estimates of the income elasticity of electricity demand ϵ_d in developing countries from the literature (Table 2) coupled with average and (future) estimated income level change to estimate growth in consumption of electricity:

$$ELCONS_{2030}^{projected} = f(\epsilon_d)$$

(Eq. 4.6)

In particular, consistently with Poblete-Cazenave and Pachauri (2019) and Fouquet (2014), a non-constant income elasticity of electricity demand schedule is considered, with declining elasticities as income (in our analysis based on income quintiles) grows.

Table 4.2: *Literature estimates of the income elasticity of electricity consumption in developing countries considered in the current analysis*

Study	Country	ε_d	Linked to
Maria de Fátima et al., 2012	Mozambique	0.69	Wealth Q1
Filippini and Pachauri, 2004	India	0.637	Wealth Q2
Tiwari and Menegaki, 2019	India	0.41	Wealth Q3
Anderson, 2004	South Africa	0.32	Wealth Q4

Based on these elasticities, we then define the effective AC consumption that could be achieved at a given income level (AC_i^{cons}) as

$$AC_i^{cons} = \begin{cases} AC_i^{techD} \; if \;\; AC_i^{techD} < ELCONS_{i_{2030}}^{projected} \\ AC_i^{techD} \;\times ratio_i \; if \;\; AC_i^{techD} \geq ELCONS_{i_{2030}}^{projected} \end{cases}$$

(Eq. 4.7)

where:

- AC_i^{techD} is the estimated technical electricity demand (without the income constraints, just based on the physical cooling needs), as detailed in the Appendix.
- $ELCONS_{2030}^{projected}$ is the total electricity consumption *i* (inclusive of ACC use) that household *i* can achieve by 2030 based on its projected income and the associated income elasticity of electricity demand ϵ_d.

Thus, If $ELCONS_{2030}^{projected}$ is sufficient to accommodate AC_i^{techD}, then we assume that the technical energy demand will be met. If it insufficient, it is modulated by $ratio_i$, defined as

$$ratio_i = \frac{ELCONS_{2030}^{projected}}{AC_i^{cons}}$$

(Eq. 4.8)

Namely, $ratio_i$ applies to those cases where AC_i^{techD} cannot be met because it is greater than $ELCONS_{2030}^{projected}$. $ratio_i$ expresses the share of potentially achievable demand $ELCONS_{2030}^{projected}$ over the locally estimated technical ACC energy consumption (AC_i^{cons}).

Note that this income constraint to is only applied to AC_i^{techD} in S0 (the empirical AC adoption scenario). For this scenario, Figure B.6 in the Appendix shows the residual unmet cooling energy demand gap as a result of income constraints. For the representative scenarios S1 and S2, the whole estimated technical energy requirement to ensure thermal comfort is considered. For the purpose of our analysis, this decision enables quantifying the economic barrier to the achievement of indoor thermal comfort.

4.3.5.2. Air circulation (fans)

In both the empirical and the representative technology adoption scenarios, fans are assumed to be adopted by all households who do not own AC. The monthly hours of fan use are set to range between a minimum of 0 and a maximum of 16 hours × 30 days = 480 hours per month. The variation in use is proportional to the CDDs experienced at location *i* in month *m* relative to the mean monthly CDDs in the entire year. The fan is modelled as a 70W appliance absorbing continuous peak power, and thus consuming 0.07 kWh/hour of use. Note that a fan is not a perfect substitute to an AC system. Fans do not cool the surrounding space and thus do not truly mitigate CDDs. They however move air and disperse humidity, which still help dealing with high temperatures.

4.3.6. Sensitivity analysis

Sensitivity of the electricity requirements and potential CO_2 emissions is carried out over two crucial parameters: the base temperature T_{base} and the energy efficiency ratios (EERs) of the representative urban and rural houses. The parametric space of the sensitivity analysis is summarised in Table 3. The baseline value is listed in bold.

Table 4.3: *Parameters considered in the sensitivity analysis*

Parameter	Values
Tbase (°C)	22, 24, ***26***, 28
EER (urban)	2.2, ***2.9***, 3.2
EER (rural)	2, ***2.2****,* 2.9

4.3.7. Geospatial electrification modelling

We implement the Open-source Spatial Electrification Tool (OnSSET) geospatial electrification model introduced in Mentis et al. (2017) and updated in Korkovelos et al. (2019) to evaluate the *ceteris paribus* relevance of considering different demand scenarios, both with and without ACC and based on different baseline values, for: (i) the optimal electricity access planning technological set-up; (ii) the power generation capacity requirements; and (iii) the investment needs.

OnSSET is a bottom-up electrification planning tool that estimates the locally least-cost energy access system (namely, the technology with the lowest levelized cost of electricity) at every geographically defined location of a region for the achievement of electricity access goals. The tool takes as inputs spatially-explicit datasets (reported in detail in Table C.2 with the corresponding sources for the data used in this analysis), including the local renewable energy potential, the price of diesel in every settlement, additional information such as distance from the currently existing transmission grid, and – crucially to the aims of the current analysis – the electricity demand at each grid cell. The technology choice space includes central grid expansion and densification, mini-grids powered by solar PV, wind, hydro or diesel, or standalone PV systems and diesel generators. Details about the functioning of the model are reported in the official documentation of the model at *https://onsset.readthedocs.io*. In this paper, the analysis is carried out at a 1 km resolution, meaning that optimisation is carried out recursively for each real unit.

Table 4.4 summarises the parametric space for the scenarios considered in the electrification analysis, which are derived from the interplay of (i) the baseline demand, differentiated in urban and rural settlements and imposed top-down referring to the electricity consumption levels from the World Bank Multi-Tier Framework (Bhatia and Angelou, 2015); (ii) the ACC appliances adoption scenario, which as described above determines the share of households at each grid cell adopting either air conditioning systems or fans for air circulation purposes; and (iii) the underlying climate change scenarios, based on the monthly local CDDs and expressing the location-specific energy need to mitigate excess heat. NoAC scenarios only consider the baseline demand; the other variants add the estimated ACC demand on top of baseline demand based on the technology adoption (determining ACC and fans adoption) and climate change scenarios (determining the CDDs experienced) interplay.

A necessary remark concerns the intertemporal dimension of the analysis: the electrification modelling aims at achieving 100% access by 2030 for the simulated scenarios. Yet, apart from the baseline climate scenario, the SSP245 and SSP370 scenarios are relative to warming levels for the 2040-2060 period. This is a deliberate choice because the objective of the analysis is assessing the planning of energy access solutions that can prove effective in mitigating future heat stress, at least over the medium-run and the systems lifetime. It is also worth mentioning that in the electricity access Tiers from the Bank Multi-Tier Framework (see Bhatia and Angelou, 2015, *Conceptualisation Report*) AC use is only considered in Tier 5, so there is no concern over double accounting of consumption. Conversely, fan use is already accounted for in Tier 2 (minimum 29.2 kWh/hh/yr), Tier 3 (minimum 87.6 kWh/hh/yr) and Tier 4 (minimum 175.2 kWh/hh/yr). These values are therefore subtracted to avoid double fan consumption accounting.

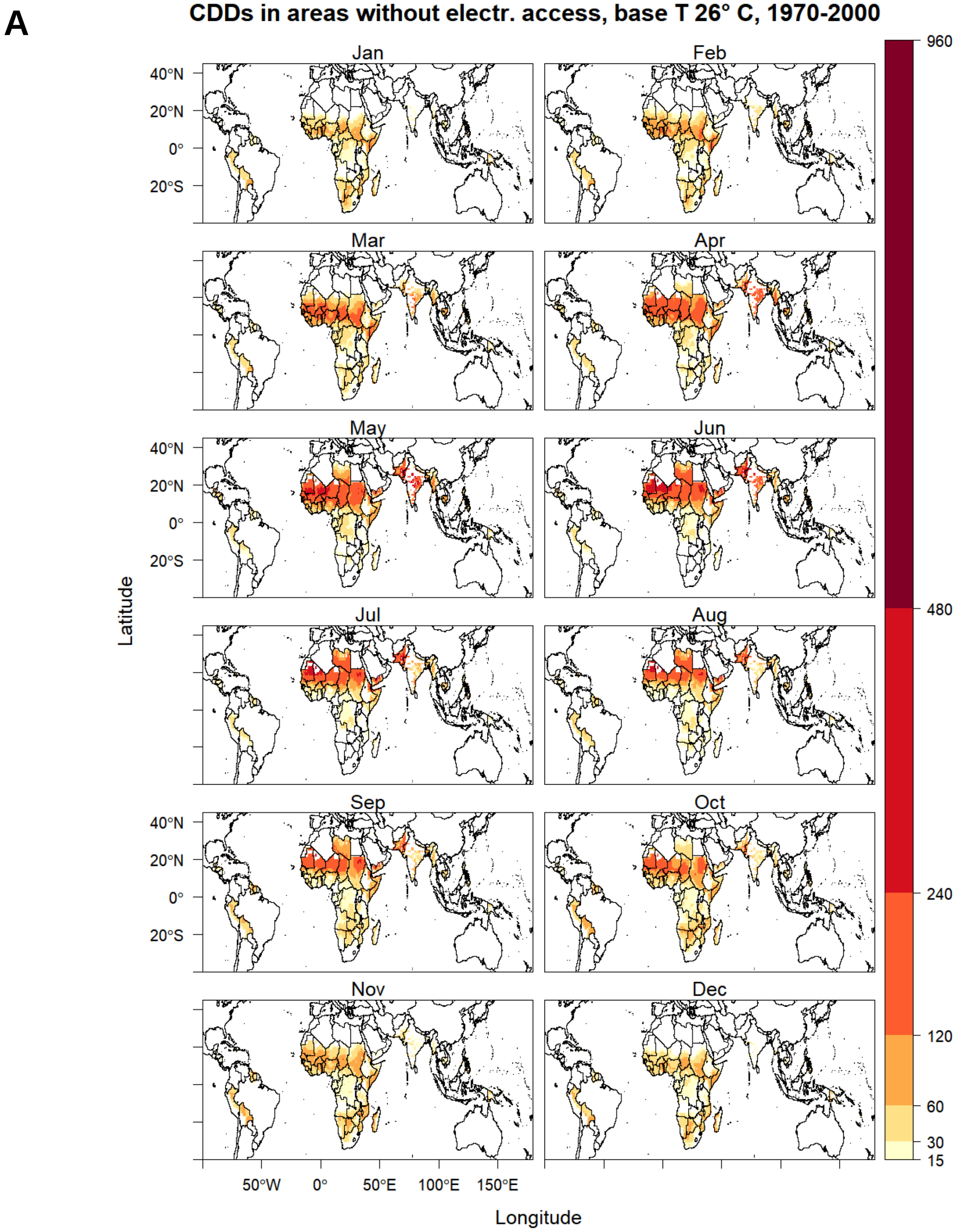
Table 4.4: *Parameters considered in the geospatial electrification analysis*

Baseline demand (kWh/hh/yr)	**Tech. adoption scenario**	**Climate change scenario**
U: 1250; R: 365; U: 365; R: 73	noAC, Empirical (S0), S1, S2	Baseline, SSP245, SSP370

Finally, Table C.1 details the assumed average techno-economic specific parameters, which refer both to the general analysis (such as the discount rate, which is set in line with the yield of long-run governmental bonds of SSA governments as reported at *https://www.investing.com/rates-bonds/african-government-bonds*), the specific electrification technologies represented in the model.

4.4. Results

4.4.1. Potential ACC services demand and energy poverty



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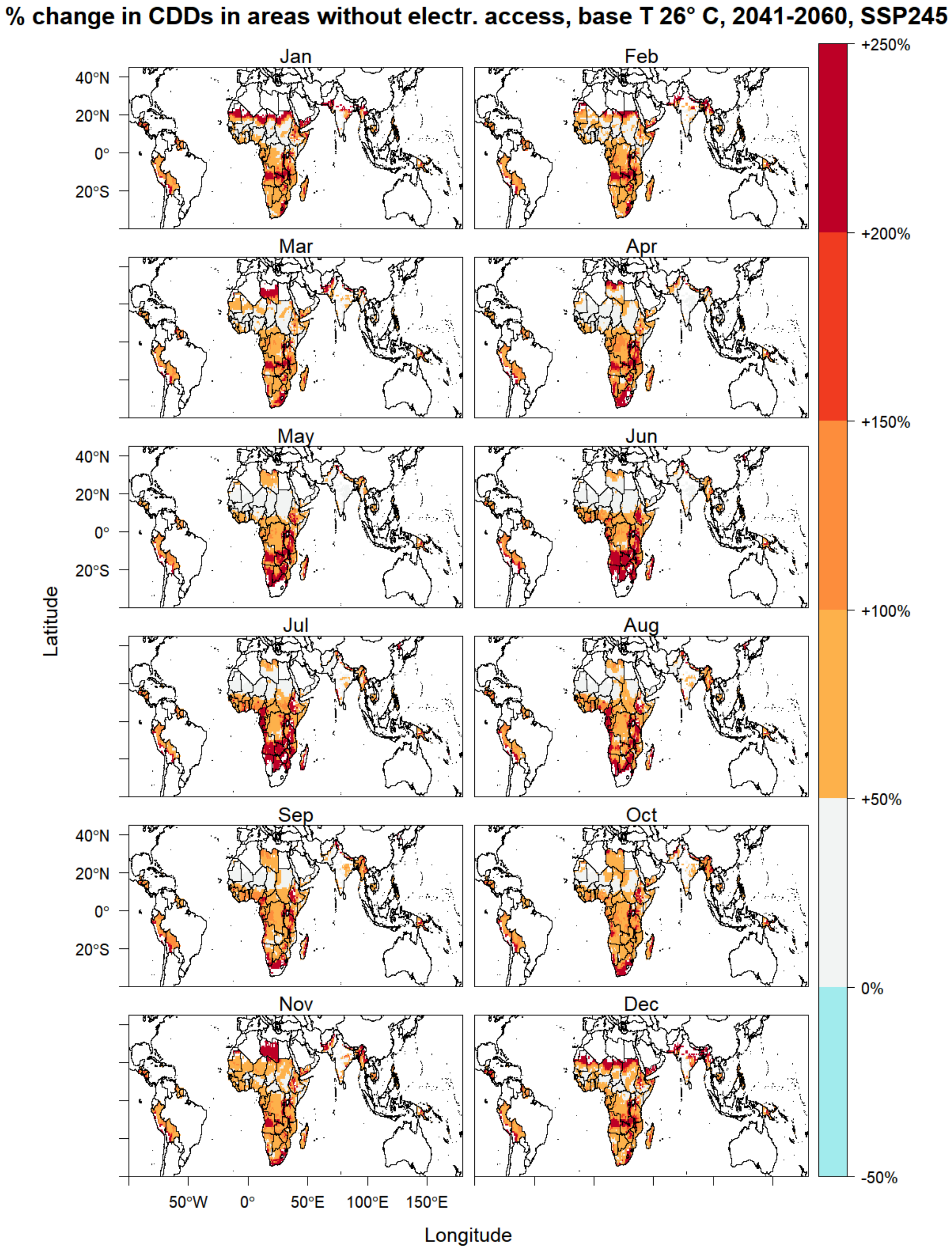
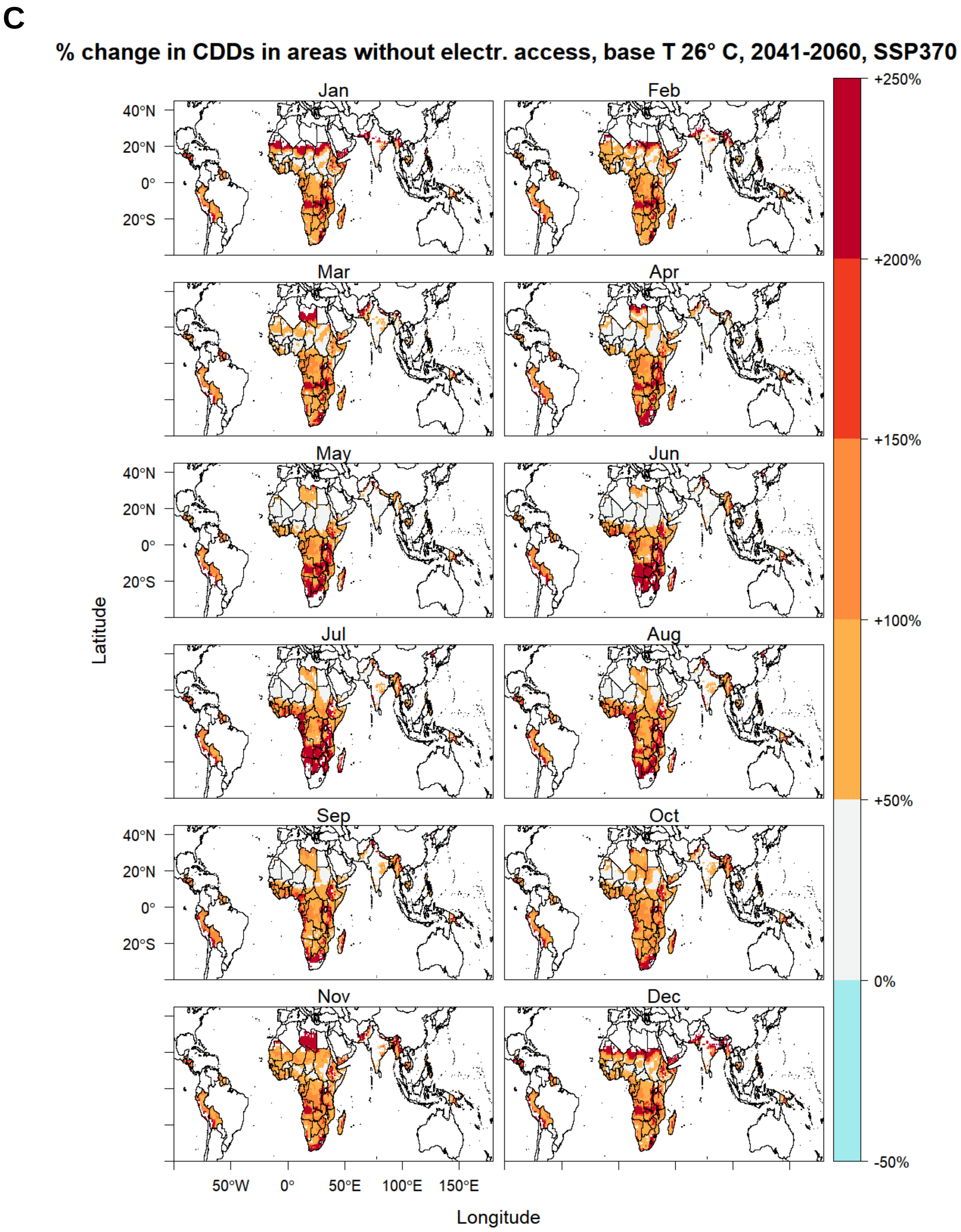

% change in CDDs in areas without electr. access, base T 26° C, 2041-2060, SSP245
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
40°N
20°N
0°
20°S
Latitude
50°W
0°
50°E
100°E
150°E
Longitude
+250%
+200%
+150%
+100%
+50%
0%
-50%



C

% change in CDDs in areas without electr. access, base T 26° C, 2041-2060, SSP370

Figure 4.3 | Average monthly CDDs for the 2020 and 2040-2060 period in areas with electricity access deficit. ***(A)*** *Historical CDDs based on WorldClimate 1970-2010; (**B)** Projected % change in CDDs for CMIP6 output from the eight CMIP6 GCMs considered forced on SSP245;* ***(C)*** *Projected % change in CDDs from the eight CMIP6 GCMs considered forced on SSP370.*

Figure 4.3 summarises the results of the calculation for both the present and future climate change scenarios. Globally, CDDs in areas currently without electricity access exhibit considerable spatiotemporal variation across regions and seasons (**Figure 4.3A**). On average, at T_{base} = 26 °C households without access to electricity are currently experiencing 450 CDDs/yr of unmet cooling. Notably, three quarters of the populations without access experience only about one sixth of the global unmet CDDs due to electricity access deficit. Conversely, nearly half of the CDDs are faced by just about 10% of the population without access. This implies that in those areas it is particularly crucial to plan for technological solutions to provide electricity access that are compatible with the provision of ACC services.

In the first months of the year, unmet CDD hotspots are observed in the regions near the Equator and in Southern Africa. In the following months, a strong intensification is observed in the Sahel and South-East Asia (e.g. India, Bangladesh) until the onset of the rainy season. The last months of the year display a less extreme but also more widespread diffusion of unmet CDDs across global hotspots of electricity access deficit. In absolute terms, the Sahel stands out as the region with the absolute highest number of unmet CDDs. On the other hand, East Africa is the region with an electricity access deficit that displays the least ACC requirements throughout the year. Additional details on the country-level yearly distribution of unmet CDDs is found in Figure B.1 in the Appendix**,** both in terms of the absolute number of CDDs (Panel A) and relative to the number of people living without access to electricity (Panel B).

Concerning the future evolution driven by anthropogenic climate change (using data from the CMIP6 simulations for 2041-2060 under the SSPs 245 and 370 scenarios), CDDs will grow robustly worldwide. If assuming *ceteris paribus* climate change, households currently without electricity access might become exposed to 715 CDDs/yr by 2050; the strongest intensification will likely be observed in large parts of Southern and East Africa in June-August. The maps in Figures 3B and 3C also provide evidence of the difference between the two warming scenarios considered in terms of the relative change from a today's baseline in terms of unmet CDDs in current electricity access deficit hotspots. Finally, Figure B.1C in the Appendix plots the absolute change in the CDDs in the current situation with the potential growth to 2041-2060 under SSP370. The results reveal that the harshest consequences of anthropogenic global warming on cooling needs (thus also depending on the exposed population without electricity access) are expected in Nigeria (+25,000 million CDDs)[1], the Democratic Republic of Congo (+15,000 million CDDs) and India and Sudan (both at about +10,000 million CDDs). Greater detail on the distribution of CDDs across months of the year across the three scenarios considered can be drawn from Figure B.2 in the Appendix. Sensitivity analysis results based on daily historical data and wet bulb CDDs, both at a higher resolution of 0.25° (Mistry, 2019a, 2019b), are reported in the Appendix D. A csv file containing the monthly estimated country-level CDDs in areas without electricity access for the three primary data sources of historical temperature considered is provided as a Supplementary File.

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[1] These figures refer to the CDDs times the population experiencing them.

4.4.2. **Potential electricity requirements for ACC services**

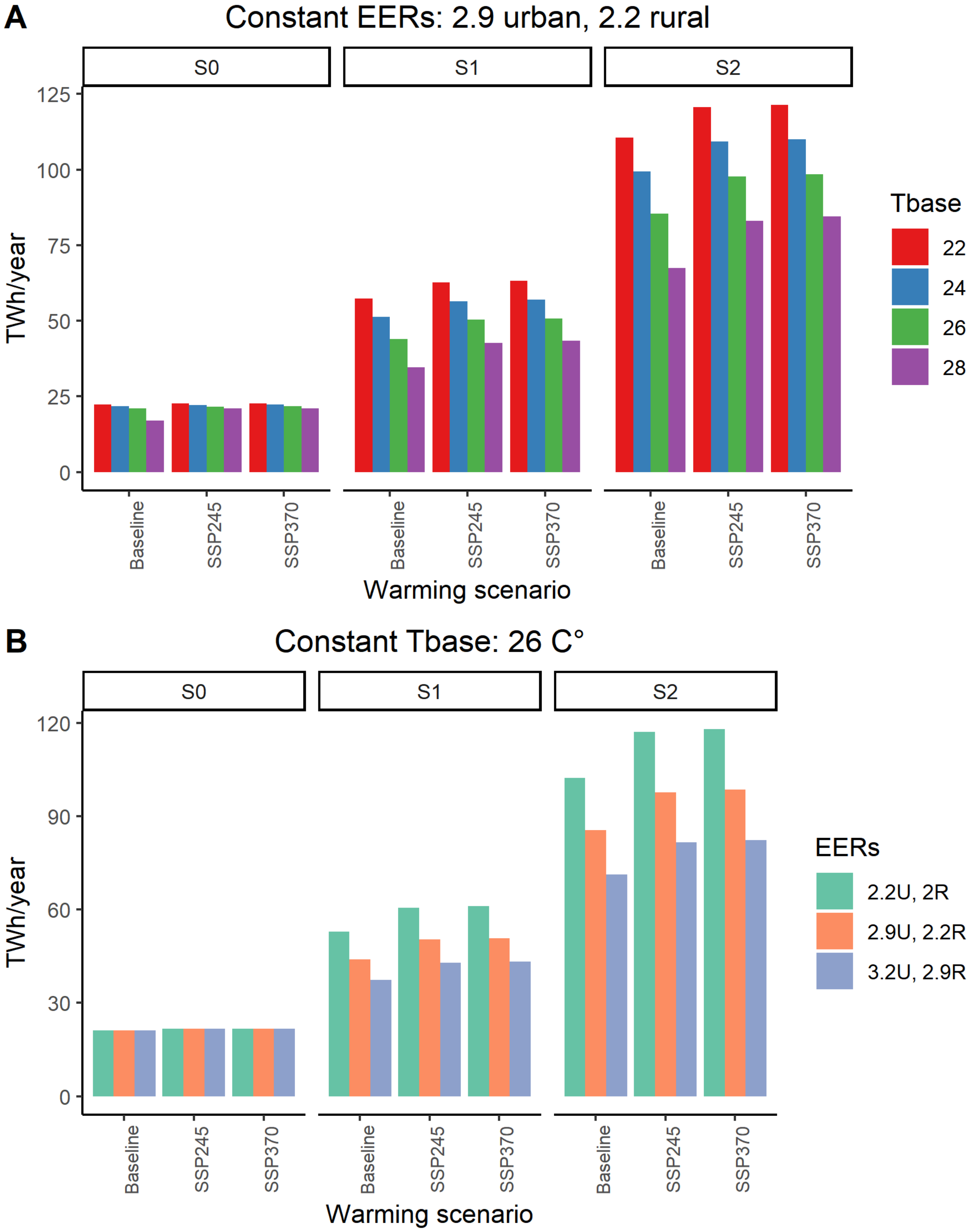

Figure 4.4 | Average yearly potential ACC electricity demand from households currently without electricity access in sub-Saharan Africa under the assumed parameters for three technology adoption scenarios and three climate scenarios (baseline, SSP245, SSP370). (A) *Results under different T_{base} (comfort temperature) targets;* ***(B)*** *Results under different AC-unit EERs (energy efficiency ratios) variants, where U and R are the assumed EERs of AC units of urban and rural households, respectively.*

The summary of the results of the energy demand assessment for the different technology adoption and global warming forcing scenarios are displayed in Figure 4.4 for a set of T_{base} comfort temperature targets (the baseline value being 26 C°) and AC-unit EERs (energy efficiency ratios). The numbers refer exclusively to households currently without access to electricity in the sub-Saharan African region. Grid-cell scale maps of the results are visualised in the Appendix B.

The assessment reveals that the empirically modelled appliance adoption and electricity demand scenario implies significantly lower demand than what would be needed to meet the policy targets of S1 and S2, where higher AC penetration rates are simulated and their use is not bounded by household income but only by the physical needs to mitigate indoor thermal discomfort. The results for the current climate and an indoor temperature objective of 26 C° range from about 25 TWh/yr to nearly 100 TWh/yr, highlighting this large cooling gap. T_{base} is found to exert a significant impact on energy demand across all scenarios, while climate change becomes a significant driver of energy demand only in S1 and S2, as S0 displays too low AC penetration rates to observe a large impact. The same pattern is observed for the sensitivity analysis over the efficiency of AC units adopted, where for S1 and S2, at constant T_{base}, the key role of AC unit efficiency stands out as a pivotal factor in determining energy demand outcomes. Overall, the results suggest that the electricity requirements are very sensitive to appliance adoption and thus income. If AC penetration is bounded by the global historical income-adoption relationship and AC use is restricted to the range of income elasticity of electricity demand in developing countries, then thermal discomfort will persist for decades even if universal electrification is achieved. Conversely, if different pathways are followed, e.g. pushed by policy support, technology cost reduction or faster economic growth, outcomes similar to those described by S1 and S2 could be witnessed, with a significantly greater energy demand. To complement the analysis, in the Appendix B we report the estimated CO_2 emissions from ACC use in each scenario considered.

The results of our bottom-up calculations are in line with the recent regional estimates (IEA, 2018), that project Africa will witness an increase in air circulation and cooling electricity demand from the current 11 TWh to 112-223 TWh/yr by 2040 depending on the efficiency of appliances and their use and of buildings. Yet, it must be remarked that the numbers reported in those studies also include air cooling energy needs from household who have electricity at home but lack ACC appliances at home, while our estimates are a subset of those comprehensive figures, as they are only relative to households currently without electricity access at home. Another comparison can be made with the regional estimates from Mastrucci et al. (2019), that project a consistent cooling energy gap of 135 TWh/yr for sub-Saharan Africa.

4.4.3. Role of ACC services for electrification planning in sub-Saharan Africa

Energy demand is a crucial variable in electrification planning, and in particular in defining the outcome of the trade-off between central grid expansion and the uptake of decentralised solutions (mini-grids or standalone generation technologies), the power generation capacity requirements, and therefore the overall investment requirements. Previous regional-scale assessments over the optimal electrification strategy in sub-Saharan Africa have highlighted a relevant share of standalone solutions : the IEA’s *Africa Energy Outlook 2019* (IEA, 2019a) argues that mini-grids and stand-alone systems will serve 30% and 25% of those gaining access by 2030, respectively. Namely, for more than half of the households currently without electricity access, the problem could be solved thanks to decentralised energy technologies. According to Dagnachew et al. (2017), depending on the consumption target, standalone systems (dominated by solar home systems with battery storage) account for between more than 40% (at Tier-1 target) and less than 5% (at Tier-5 target), with mini-grids in all scenarios accounting for less than 10% of the new connections. Levin and Thomas (2016) find that that given current technology costs, central grid expansion is extensively required to enable higher levels of consumption, but they express confidence that technological cost reduction trends will disrupt the paradigm, with a potential leapfrog of the centralized electrification paradigm.

Our ACC-related potential electricity demand estimates allow to explore the tight interconnections between SDG 7’s electricity access target and ACC needs. We calibrate a geospatial electrification model for sub-Saharan Africa, the global hotspot of electricity access deficit (hosting over 75% of the global population without electricity access, IEA and IRENA, 2019), and add the local ACC electricity requirements for the different warming and technology adoption scenarios on top of a set of baseline yearly household electricity consumption. The model is forced to provide universal household access to electricity by 2030 under the different demand scenarios considered. Note that the model projects heterogeneous urban-rural population growth to 2030 (Table C.1) and thus also total ACC energy demand.

Recent empirical evidence (Bensch et al., 2019; Chaplin et al., 2017; Hoka Osiolo et al., 2017; Lenz et al., 2017; Taneja, 2018; Tesfamichael et al., 2020) suggests that communities gaining access generally consume little electricity, with most household consuming between Tiers 2-3 in rural areas and between Tiers 3-4 in cities, with reference to the World Bank Multi-Tier Framework for Measuring Energy Access (WB-MTF). Tiers 4, 3 and 2 imply consumption levels of 423, 160, and 44 kWh/HH/yr, respectively. Our baseline consumption targets are therefore set around these values – as policymakers and companies will likely be prone to invest their resources optimally when sizing electrification solutions – , on top of which we add ACC energy needs according to our ACC appliances adoption and climate scenarios. Detailed information about the electrification analysis approach, the techno-economic assumptions, and the data sources is provided in the Materials and Methods section. The final aim of the assessment is to evaluate the role of the estimated ACC energy requirements on the optimal technology set-up and investment requirements to achieve universal electrification.

Our results (Figure 4.5A) show that accounting for the estimated ACC needs on top of baseline residential consumption targets implies a 4.5 [0.4 – 9.3]% scenarios-mean reduction in the share of decentralised systems as the least-cost electrification option by 2030. The mainly regards the trade-off between central grid extension and standalone energy access systems. The shift is mapped in Figure 4.6 for a representative shift between scenarios of equally low baseline demand but differentiated ACC appliances adoption (noAC and S2). While the impact of considering cooling energy on the optimal electrification systems set-up is relevant, the most remarkable impact is observed on the investment requirements to achieve universal electrification (Figure 4.5B).

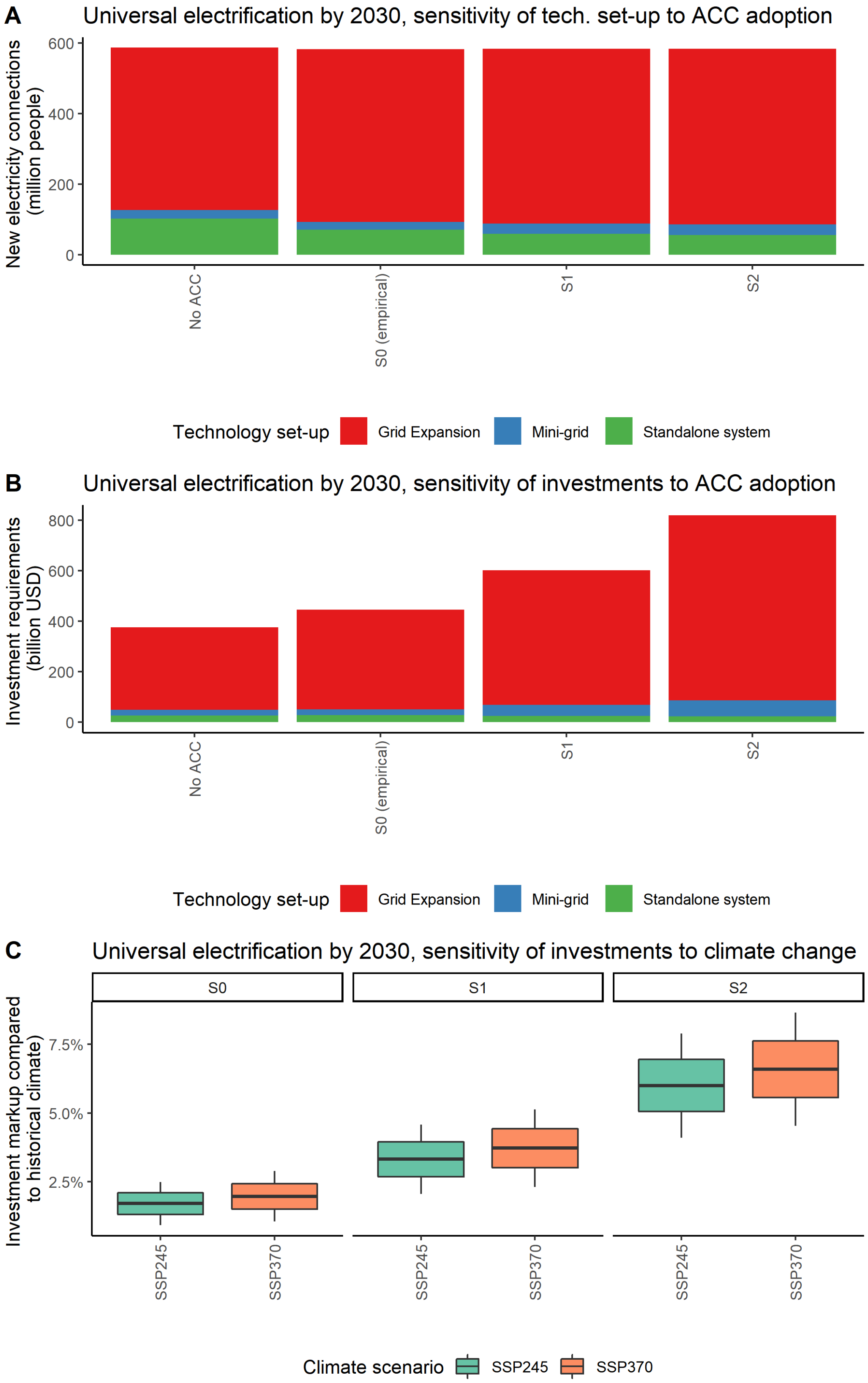

Figure 4.5 | Results of the geospatial electrification analysis under a universal electrification by 2030 target. (A) *Optimal technology set-up (% of new connections)*

across a variety of demand scenarios and electrification systems under different ACC appliances adoption scenarios. ***(B)*** *Cumulative investment requirements for electrification (bn. USD) under different ACC appliances adoption scenarios****; (C)*** *Investment mark-up (% increase) as a result of climate change compared to historical climate conditions.*

As a result of both the different optimal electrification technology set-up to supply the required energy demand itself, and – to a much larger extent – of the growing load and power consumption under growing AC adoption, the scenario-mean investment ramps up considerably (+65.5 [18 – 118]%) with growing AC adoption. Cumulative investment requirement to 2030 range from a low of about $146 bn ($14.6 bn./yr) under *t32* baseline demand and no AC needs inclusion, and nearly $1,058 bn ($106 bn./yr) for a scenario of high baseline demand (t43), substantial air conditioner systems uptake (S2), and a warmer climate (SSP370). Finally, as shown in Figure 4.5C, climate change alone increases the scenario-mean investment requirements by 4 [1 – 8.7]%.

Figure 4.5C is particularly insightful because it allows disentangling the role of future climate change scenarios (by comparing the two coloured bars within each facet of the graph, bearing in mind that the graph expresses the percentage investment growth compared to the historical climate) and the role of income or policy in driving ACC appliances adoption and use with ceteris paribus climate (comparing bars of the same colour across facets).

Due to the variety of assumptions, scenarios, baseline years, and demand targets it is challenging to directly compare these investment requirements with figures reported in previous studies. Yet, they are in the same range of variability of seminal findings (Mentis et al., 2017; Pachauri et al., 2013; PBL Netherlands Environmental Assessment Agency, 2017), suggesting that plausible techno-economic assumptions are made.

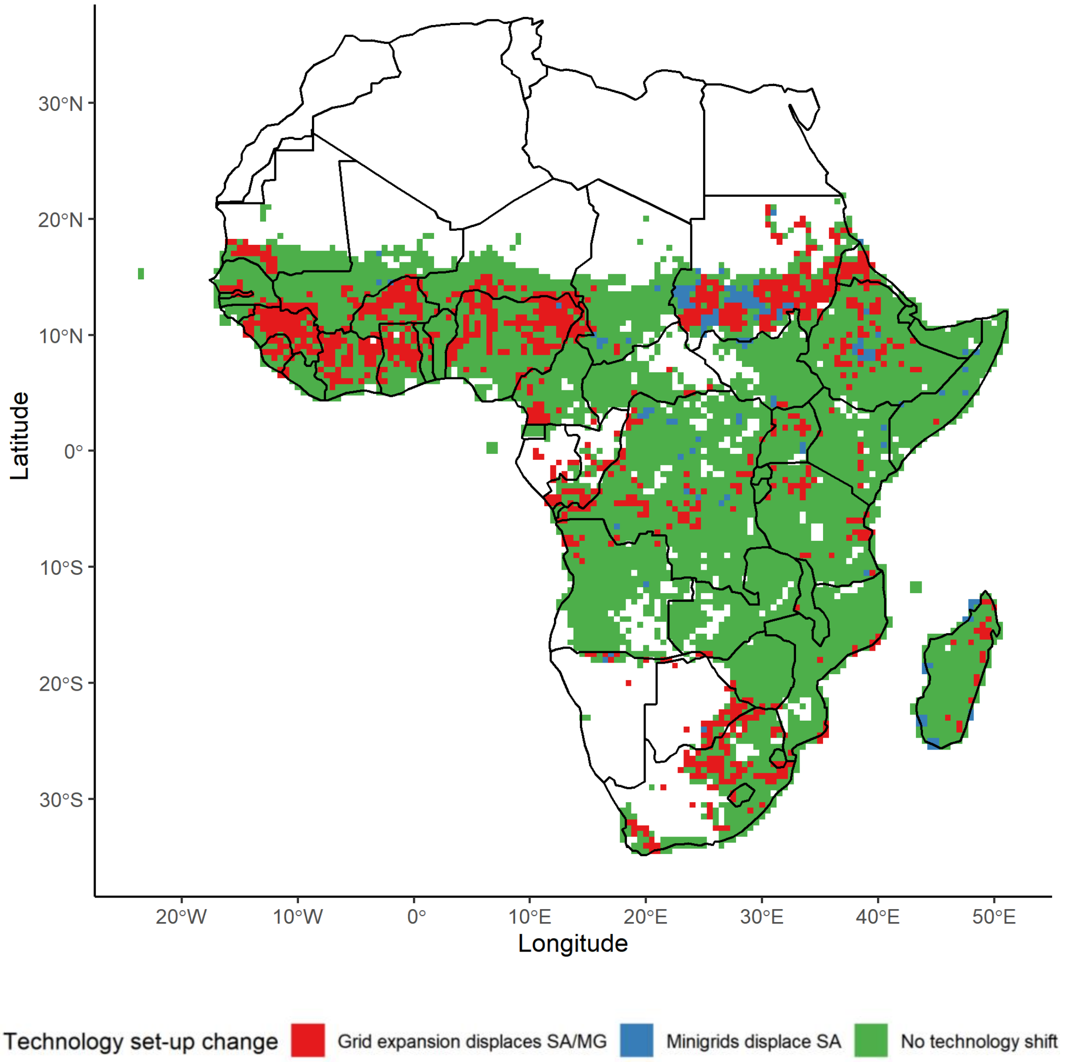

Figure 4.6 | Map of sub-Saharan Africa showing the ceteris paribus shift in the least-cost electrification set-up when considering baseline and ACC-inclusive demand scenarios.

The results of our analysis confirm that planning electricity supply effectively depends on energy demand. In turn, the results suggest that if thermal discomfort in SSA is to me mitigated, ACC services need to become much more pervasive than under a baseline scenario. In turn, in this scenario ACC use would drive a very strong increase in energy demand in the residential sector, and in particular among households that will gain access to electricity over the next decade (if SDG 7 will be achieved).

Yet, several modelling and policy inputs suggest that in many areas electricity access plans based on large-scale uptake of standalone solutions or those based on conservative demand targets appear to be the only financially viable option in the medium-run. Policymakers should however be aware that such electrification strategies will likely leave many without indoor ACC adaptation options (and therefore in persistent energy poverty), with potential repercussions on welfare and development prospects. On top of that, adjusting adaptation needs based on baseline climate conditions or future warming plays a major role in the required power generation capacity for ACC and therefore in the total investment needs. We argue that these hidden costs and benefits should receive more relevant consideration in electrification policy.

4.5. Discussion and conclusions

4.5.1. Future ACC demand from energy-poor households

In this paper we carried out a planning-oriented assessment of energy-poor household exposure to thermal discomfort. The ultimate aim is to estimate the energy requirements to meet ACC services needs among energy-poor households. We considered both an empirically grounded scenario based on expected income growth and climate change and the consequent future ACC appliance adoption and use, along with a set of archetypical, policy-descriptive scenarios.

The results from climate-energy ACC modelling show that the mix of air circulation and cooling technologies adopted by households is the single most impactful driver of energy demand: the penetration of AC systems will play a disproportionately larger role than a universal adoption of fans, even at very high intense use of the latter (as recently discussed in IEA, 2020, 2018). Our empirical modelling suggests that income is a severe constraint to AC use, unless a cost, priority, or policy-induced shift is observed in the demand-side relatively to the historical global relationship between income, AC adoption, an electricity demand. The representative scenarios model these archetypical pathways, whereby the estimated energy consumption levels are those which would be necessary to guarantee universal indoor thermal comfort. The gap between the empirical and representative scenarios is a major reason for concern for decision-makers, because it highlights the risk of persistent thermal comfort discomfort even under the expected rise in affluence of SSA countries.

Finally, irrespective of the base temperature considered, the efficiency of the installed AC units will have a very substantial impacts on energy consumption in scenarios of significant AC penetration. The topic is indeed already at the centre of recent institutional reports aiming at minimise the social impacts of future AC use (Anderson et al., 2020; IEA, 2018). Some countries, such as Ghana, Nigeria, Kenya, and South Africa, have minimum performance standards for new AC units or have banned the import of second-hand, inefficient units.

4.5.2. Policy implications for electricity access planning and investment needs in sub-Saharan Africa

Based on the wide range of ACC energy demand scenarios estimated, we carried out an SSA-wide (the global hotspot of energy poverty) spatially-explicit electricity access planning analysis. Our results show that providing universal electricity supply compatible with different ACC technologies adoption and use scenarios requires significantly larger investments than under baseline demand (+65.5 [18 – 118]%). This mark-up grows further when quantifying the impact of future climate change on energy demand for ACC: compared to the historical climate, considering SSP245 and SSP370 for the 2040-2060 period impacts the technical energy requirement to meet all CDDs experienced by energy-poor households by 4 [1 – 8.7]%.

Moreover, when adding ACC-related energy needs on top of conservative demand targets, the optimal technology set-up shifts away considerably from decentralised energy access systems. This is because decentralised energy access systems (and in particular standalone and home systems) might not be suitable to meet the high peak power requirements of air conditioning, unless very efficient appliances are adopted (IEA, 2017). In addition, a higher demand can make decentralised solutions economically inefficient compared to extending the national grid for the economy of scale dynamics involved (Deichmann et al., 2011).

They key lesson learned from this study is that planning universal household electrification without explicitly accounting for thermal comfort needs might therefore result in large energy supply deficits and persistent energy poverty even with nominal universal electrification, which might be achieved even with small-scale low-power systems. In turn, leaving millions of households with unmet (and growing) CDDs could negatively affect the broader socio-economic development of low-income countries as a result of the negative repercussions on health (physical and mental) and productivity.

These findings are not arguing against decentralised energy access systems, as these have the major advantage of allowing for minimum levels of electricity access at relatively lower price (and chiefly in areas where the grid extension would require very large investments). The relevance of decentralised systems is in fact becoming even greater thanks to emerging innovative business models (Mazzoni, 2019) allowing to abate upfront cost barriers. Energy-ladder (Chattopadhyay et al., 2015) and energy-development nexus (Riva et al., 2018) theories argue that basic energy access can provide the spark to initiate socio-economic development and allow households to ‘climb the ladder’ towards more robust energy supply systems. The empirical evidence testing the validity of these claims is however still mixed (Grimm et al., 2017; Urpelainen, n.d.). Yet, from a public policy perspective, regions receiving standalone electricity access might become less significant for policymakers in terms of investment and central infrastructure expansion priority. Therefore, irrespective of being nominally electrified, they could remain for long time in a condition of energy poverty and be unable to operate ACC services and other autonomous adaptation measures.

Overall, we encourage decision-makers (and in particular the interface between energy access institutions, such as, SE4ALL, ISA, ESMAP, Power Africa, RES4Africa; and cooling planning institutions, including Cool Coalition, KCEP, United for Efficiency, Global ABC, PEEB, Solar Cooling Initiatives) to consider ACC and other energy-consumptive adaptation actions in policies targeted at expanding electricity access and in power generation capacity planning, as these will likely be strong drivers of electricity demand growth from the residential sector in the coming years. These needs should also be reflected in national greenhouse gas mitigation policies.

4.5.3. **Main limitations**

The key limitations of this study include: *(i)* the uncertainty over the distribution of the population without access to electricity. This uncertainty comes both from the quality of the primary census data on which gridded population products are based, and the proxy nature of the global spatially-explicit electricity access assessment based on nighttime lights (Falchetta et al., 2019). *(ii)* The consideration of the CDD metric. Standard CDDs are useful for their simplicity and standard use in the climate and energy engineering fields. Yet, they overlook important dimensions affecting the perceived heat such as relative humidity and wind chill. Given the large spatiotemporal scale of the analysis, CDDs were preferred as climatic indicators. Additional results considering wet-bulb CDDs that account for relative humidity are reported in Appendix D. *(iii)* The unavoidable degree of uncertainty or arbitrariness in the ACC appliances adoption and use scenarios. While we modelled both empirically-grounded and archetypical policy-descriptive scenarios, each comes with data and scenario uncertainty. The estimates cannot be validated on real data for SSA countries, as there is no extensive data on household ACC appliance ownership and use for the countries considered in the analysis. It must be remarked that while the seminal model of McNeil and Letschert (2008) is only fit on 64 data points between 1991 and 2007, an African-specific calibration based on more recent data (e.g. from the *Integrated Public Use Microdata Series*) would not be meaningful in the context of the current analysis. In fact, projected income levels for 2050 would mostly fall outside of the calibration range (the current distribution of income levels in SSA counties) and the estimate would thus rely on a highly uncertain extrapolation. To mitigate these concerns, data and code to facilitate ready replication of the analysis, including modifications in the scenario assumptions and future ad-hoc calibration upon availability of survey data, is provided as supplementary material. *(iv)* The lack of consideration of alternative technologies such as evaporative cooler technologies and other passive buildings and urban planning options that can mitigate CDDs while requiring less energy. Note however that most of the electricity access deficit is concentrated in rural areas, where these architecture and urban planning options are less viable. Further research examining the interlink between energy poverty and ACC needs could consider these important aspects. An ad-hoc decomposition analysis – beyond the scope of this paper – could help shedding light on the degree of significance of each determinant in the optimal system outcome.

A final remark concerns the necessary consideration of aspects related to utility capacity to plan the power system and regulatory quality of the energy sector, which as benchmarked by the RISE (Regulatory Indicators for Sustainable Energy) is still lagging behind in several SSA countries. Institutional and regulatory quality are fundamental conditions for the expansion of generation, transmission and distribution capacity – including enabling private investment in standalone and mini-grid solutions (Ahlborg et al., 2015; Emery, 2003; Sergi et al., 2018). Our geospatial electrification analysis is purely techno-economic and therefore it does not specifically embed these dimension (an ongoing application in this direction is found in Falchetta et al. (2020).

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5. The role of regulatory, market and governance risk for electricity access investment in sub-Saharan Africa

5.1. Introduction

Achieving the sustainable development goals requires a substantial ramp-up of baseline investment flows (McCollum et al., 2018). The financing gap is even larger in developing countries, where progress towards several SDG targets is still lagging behind (Ritchie and Mispy, 2018). A relevant share of the estimated capital requirement is linked to the targets of universal energy access, as nearly 800 million people worldwide live without access to electricity and 2.6 billion lack access to clean cooking facilities (IEA et al., 2020). The bulk of the energy access deficit is concentrated in sub-Saharan Africa (SSA), a region emblematic of how an abundance of energy resources is not a sufficient condition for eliminating energy poverty.

Different sources have estimated the required additional annual power sector investments (including T&D lines) in SSA at $30 to $55 billion (IEA, 2019; Lucas et al., 2017) to provide electricity to the ~575 million without access in SSA. These large requirements derive from the capital-intensiveness of generation, transmission, and distribution infrastructure and its operation and maintenance costs. For instance, a renewable-based mini-grid to serve a local community can require an upfront investment of between $1,250-5,000/kW (Nerini et al., 2016); adding a kW of generation capacity to the national grid ranges between $1,000-2,500/kW, depending on the technology implemented and the plant size (according to a survey by Enerdata (2016) for projects implemented in SSA over the last decade); medium-voltage power transmission lines are estimated to cost an average $25,000/km (Karhammar et al., 2006). However, according to the available estimates, between 1990 and 2013 only $31 billion has been invested in power generation in SSA (excluding South Africa), with less than 16 GW of generation capacity added (Eberhard et al., 2016).

Several studies (Dagnachew et al., 2020; Simone and Bazilian, 2019) have argued that a set of institutional, market-related, and financial barriers are the main factors responsible for the lack of energy supply infrastructure investment. As a result of these barriers, fundamental uncertainty remains over the sources of the required financing flows to the energy sector. This uncertainty is partly due to limited governmental investment in SSA, due to both low public revenues as share of GDP (World Bank, 2018) and high yielding national bonds (in most countries long-run bonds yield >15%, Investing.com, 2020). Lending large amounts of money at these rates would determine an escalation of public debt, which simply cannot be guaranteed. Given the limited opportunity of governments in providing finance, a crucial question is what the role of the private sector could be. The propensity of private players in the energy sector to seek business opportunities and thus meet the local demand for investment crucially depends on their perception of the local investment environment, which is influenced by – among others – regulatory and institutional quality and political stability (Iyer et al., 2015; Schmidt, 2019). Companies internalize a discount rate in their investment decisions (Schleich et al., 2016) which is strongly affected by the degree of risk that they perceive in a given setting (Ryan and Gallagher, 2006). In turn, this discount rate also mirrors the (implicit) discount rate of households when they decide upon their energy-related investment (Reddy, 1996). By implicit discount rate we broadly mean "*preferences, predictable (ir)rational behaviors and external barriers"*, quoting the energy-related definition provided in (Schleich et al., 2016).

An example can clarify what this type of private (energy-related) discount rate refers to in the context of this paper. Suppose investor *X* wants to invest in an energy project in country *Y* and can lend money at an interest rate *i* of 10%. However – given the local governance structure and other political and market risks – the implicit discount rate *r* of the investor at which the project is discounted throughout its lifetime is higher (say, 20%). As a result, even though the expected rate of return (ERR) of the project is e.g. 12% (greater than the lending interest rate), the investor decides not to invest because $i < ERR < r$. In principle, functioning capital markets should internalize all risk components in the lending interest rates and $i = r$ should hold. Yet, in the context of developing countries and development investments, the market interest rate could be of a country or source different from the project's location. Alternatively, even when capital is lent from the national capital market, in the case of private, small-scale energy access investments, the private discount rate is generally not equivalent to generic lending rates, as companies need to internalise the array of additional, project-specific risks in their project cost-benefit analysis. Historical lending rate data for specific private energy access investments could offer a picture of these private discount rates, but these data are simply not accessible in a systematic way.

In this context, this paper proposes a methodology to explicitly account for investment risk perceived by private players and it applies the approach to determine its impact on the optimal technological mix and investment requirements for universal electrification in SSA. We introduce a composite index of regulatory quality – the Electricity Access Governance Index (EAGI) – based on a large array of information on regulatory quality, governance, and stability. This index is used to estimate the energy access investment discount rate and applied in the bottom-up electricity planning model TIMER (Dagnachew et al., 2017; Stehfest et al., 2014; van Ruijven et al., 2012) within the framework of the IMAGE integrated assessment model (Stehfest et al., 2014, p. 0) for the SSA region. The EAGI embeds the role of the energy sector regulatory quality, as well as the general governance, investment environment, and political stability, and it determines the implicit energy investment discount rates.

The main objective of the paper is therefore to explore the impact of adjusting the baseline discount rate to country-specific sources of investment risk on the cost-efficient technology set-up (and primarily the trade-off between central grid expansion and decentralised solutions procurement) and investment requirements for achieving universal electricity access in SSA. The study aims at filling the literature gap found in recent model-based research assessing optimal electricity access supply options and investment requirements with a spatially-disaggregated approach. The latter research has focused largely on techno-economic dimensions (Dagnachew et al., 2017; Ellman, 2015; Mentis et al., 2017), without explicitly encapsulating the heterogeneity in the investment environment quality. The only notable exercises that have begun taking this direction are the recent work in (Korkovelos et al., 2020), (Spyrou et al., 2019), and (Patankar et al., 2019), who modelled the role of conflict in electrification and power systems planning.

The remainder of the paper is structured as follows. Section 2 carries out a targeted literature review of the key dimensions assessed in the proposed methodology, namely private sector electricity access investment in SSA, the role of governance for private sector investment, and – more specifically – the significance of the discount rate as a measure of investment risk. The literature screening provides an understanding of the key drivers and consequences of risk for investors in the electricity sector in the context of developing countries. These factors are then embedded in the empirical analysis in Section 3, where we introduce the data and the methodology, which is divided into the EAGI index formulation and its implementation in the electrification model through its conversion into an implicit discount rate. Section 4 and 5 present and discuss the results, respectively. Section 6 concludes.

5.2. Background and literature review

5.2.1. Private investment in the power sector of Sub-Saharan Africa

Between 1990 and 2013, only 16 GW of generation capacity were added throughout SSA (Eberhard et al., 2016). These power plants have been predominantly procured by independent power producers (IPPs) (Eberhard and Gratwick, 2013) and financed by governments and multilateral development banks. While over the last ten years Chinese funding (enabled mostly through Chinese state-run banks lending to Chinese state-run companies; see (Powanga and Giner-Reichl, 2019) has become the first source of investment after direct governmental investment in the power sector of SSA (Eberhard et al., 2016), in the same period there has been only a moderate upward trend in IPP investment flows.

One of the most notable attempts to collect information and shed light on investment flows is (Eberhard et al., 2017). The authors show that while IPPs (Independent Power Producer) have invested growing amounts of capital in energy project in SSA (more than 0.7 billion USD in 2014), the bulk of the recently added new generation capacity procured by private or foreign players has been concentrated in only 15 of the nearly 50 countries of SSA, notably in Nigeria (about 1.5 GW), Kenya (1.1 GW), Ghana (about 1 GW), and Cote d'Ivoire (900 MW). These statistics offer a glance of the ongoing investment trends, but the lack of a public and systematic database of private sector investment flows into the energy sector of countries in SSA hinders a clear and up-to-date understanding of the situation and its evolution. In turn, this lack of information is reflected in the paucity of academic literature analysing energy-related investments flows in SSA to understand their drivers and impacts.

Another crucial factor to consider is the substantial evidence of an important role of peering dynamics in investment decisions (Zaighum and Karim, 2019), where companies follow companies and systematically target their infrastructure projects towards certain countries and regions where there is already a vivid investment environment. This can be described as a way to reap the positive externality of the information collection costs previously incurred by the company itself or by its competitors (Chen and Ma, 2017).

5.2.2. The role of governance for private investment

In the context of the power sector of SSA, investment can be represented as a function of uncertainty and reward, with the financial risks and barriers to electricity infrastructure emerging at different scales [32]. Namely, through *micro* factors – which include factors at the project or infrastructure level –, *meso* factors, encompassing national aspects such as regulation or assets, and *macro* factors, which are linked to global dynamics such as exchange or interest rates. Meso-factors are the crucial ones for the scope of the analysis we present in this paper, because the quality of governance and the political stability directly affect the amount and nature of investment in a country through their impact on the degree of uncertainty for business and thus the final costs they incur in (Eifert et al., 2005; Emery, 2003; Ramachandran et al., 2009).

A broad stream of literature has engaged with the analysis of the role of governance for attracting private-sector investment. Eberhard et al. (2017) (Eberhard et al., 2017) discussed how planning, competitive procurement and contracting, risk mitigation, credit enhancement, power markets, and regulation are the crucial explanatory factors for the level of private investment. Sergi et al. (2018) (Sergi et al., 2018) showed that national institutions and governance have a considerable impact on the development of different electricity access technologies. They compared the example of Kenya, where power sector unbundling and privatization efforts have mostly attracted private investment in on-grid projects, with the case of Tanzania, where less tight regulations for off-grid power producers are in place, including clearer regulatory framework for imposing cost-reflective tariffs to households connected to mini-grids. They argue that the latter regulatory environment creates a more supportive environment for niche innovation, which is reflected in the thriving mini-grid sector in Tanzania, which not by chance counts the most mini-grid customers (ESMAP, 2019).

Empirical evidence from pay-as-you-go (PAYG) solar home system contracts subscribed in Benin shows that PAYG service providers target credit-worthy consumers with the implicit objective of reducing their investment risk. The authors argue that these results cast doubts as to whether PAYG (and in general privately-provided decentralised energy access solutions) bridges the "last mile" electrification gap. These doubts are also fed by the fact that nearly all PAYG customers in the country are within short physical distance from the grid but choose the PAYG services because of service reliability and affordability.

Afidegnon (2019) investigated the success factors for power project development businesses in SSA. He collected data from semi-structured interviews to explore the strategies used by executives of four companies in SSA who successfully developed power projects within the last 5 years. His results show that the interviewed CEOs attached great significance to the development a deep knowledge of the target market and aligning the stakeholders’ expectations using a combination of local partnership and international consultants. Moreover, CEOs attributed a foremost role to ensuring the commercial viability of the project through bankable project agreements and the implementation of appropriate risk management and credit enhancement tools.

The evidence and arguments collected in this literature screening provides the basis for the data collection for the construction of the EAGI discussed in Section 3.

5.2.3. The discount rate as a measure of investment risk

To factor qualitatively perceived risks – such as those stemming from a low regulatory quality – into structured models of investment decisions, these risks have to be translated to a quantitative measure. A seminal contribution by Hirshleifer (1961) (Hirshleifer, 1961) introduced a market theory of risk, proposing to expand the theory of present value maximisation by modifying the discount rate to account for the risk component of investments. According to this theory, investments are discounted by a baseline risk-free rate (Lintner, 1969) that accounts for the pure value of time – i.e. the trade-off between consumption in the present and the future –, on top of which a risk premium is added. The latter takes into consideration the additional sources of risk that the investor perceives in the context of the project under examination, but which not always are encapsulated in the market interest rate.

Yet, there is no standard methodology to translate a qualitatively perceived risk – such as political instability, corruption, low regulatory quality, currency inflation and consumer debt repayment issues – into a risk-adjusted discount rate. This is because of the large variety of potential sources of risk, which are often project-specific. Also for the specific case of private infrastructure investment, there are no set guidelines for determining the discount rate (Short et al., 1995). A 2015 survey on valuation methodology in Africa (PWC, 2015) inquired into how the private sector incorporates risk in the valuation of an investment. This analysis showed that most respondents incorporate risk associated with infrastructure projects in Africa in the discount rate. For capital-intensive projects, it is often the case that multi-national or foreign companies have access to capital in markets with significantly lower interest rates than in most countries of SSA, and yet they must encapsulate the risk of investing in a foreign country into their investment decisions. A survey carried out in 2018 (Grant Thornton, 2018) among utility-scale renewable energy developers in SSA in Kenya, Nigeria, and South Africa inquired on the discount rate used in potential ground-mount solar and onshore wind market projects, finding values in the range of 14.75-18%.

Yet, when considering smaller-scale energy investments carried out by private actors, the role of additional sources of risk becomes crucial and is likely not encapsulated in the capital market. Private discount rates include both sector-specific risks and the implicit discount rates of households when they decide upon their energy-related investment (Train, 1985), i.e. the payback time they are willing to accept. Empirical evidence has shown that the applied discount rates for fuel choices are much higher for low income households (up to 80%) that for affluent households (down to 10%) (Daioglou et al., 2012). Seminal contributions specific to the role of the discount rate in energy access and energy carrier choices decisions include the work of Reddy (1996) (Reddy, 1996), who modelled the relationship between household income and energy carrier choices, showing that households shift from one energy carrier to another if their income increases and that the consumer discount rates decrease exponentially with household income.

5.3. Materials and methods

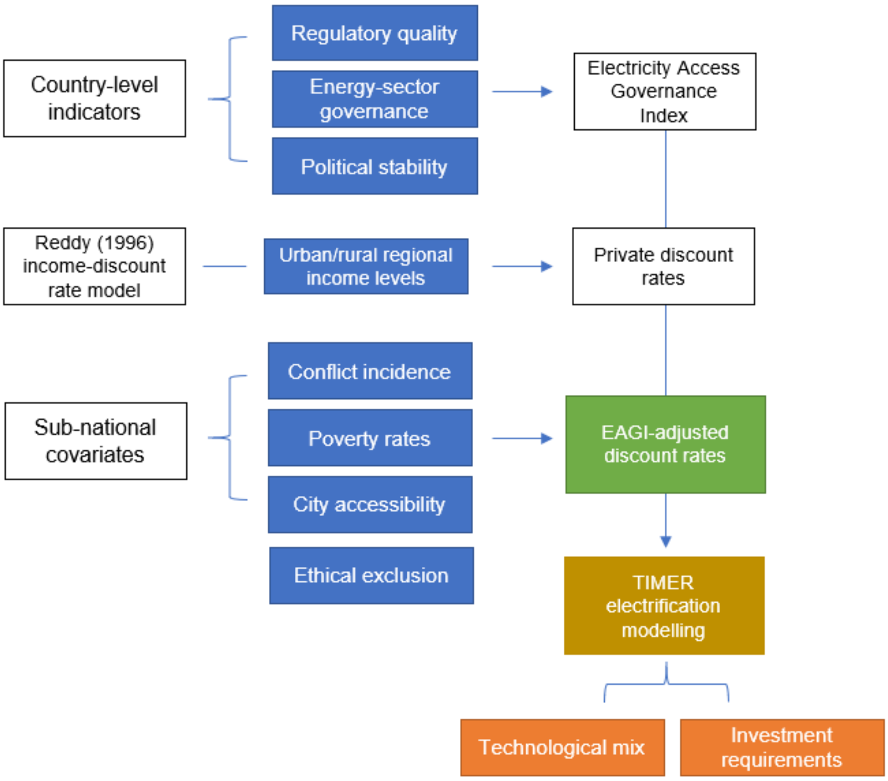

Figure 5.1: Conceptual framework for the methodology adopted in this study. The framework illustrates the data inputs (in blue), the data modelling steps (in white), the intermediate outputs (in green), the electrification analysis (in yellow), and the final results (in orange). Source: author's elaboration.

Building on the evidence found in the literature on the key sources of risk affecting private discount rate in energy access investment, here we enrich a conventional electrification analysis with regulatory, governance, and political factors (Figure 5.1). Factors that are strong predictors of electricity access (Bonan et al., 2017; Khennas, 2012) and private sector investment (Asongu and Nwachukwu, 2015; Drogendijk and Blomkvist, 2013; Hornberger et al., 2011; Ndikumana and Verick, 2008) are summarized into an Electricity Access Governance Index (EAGI; Section 5.3.1) which is then used to simulate the role of regulatory quality on investment decisions via the discount rate (Section 5.3.2). For selected countries, an in-depth country exercise is carried out to characterize sub-country heterogeneity in the propensity of private players to invest in different regions of a country. These are detailed in Section 5.3.3. As detailed in Section 5.3.4, The EAGI index is then fed into the TIMER simulation model, which yields results over optimal technological mix and investment requirements in every grid cell. Section 5.3.5 describe the data and scenarios considered in the current analysis, while Section 5.3.6 highlights the underlying mechanisms through which changes in the discount rate affect the optimal electrification planning.

5.3.1. The Electricity Access Governance Index (EAGI): Input data and indicator aggregation

Based on literature screening, we consider socio-economic factors that are correlated to the levels of electricity access in SSA and regulatory and governance-related factors that are specific to private sector investment decision making, with a particular focus on renewable energy and off-grid technologies. Indicators are chosen based on data availability and quality; only indicators with recent (post 2010) data available are considered suitable due to the rapidly developing nature of the electricity sector in SSA. Table 5.1 summarizes the input data sources used for the EAGI formulation. These are explored in greater detail with descriptive statistics and graphs in the Supplementary Materials.

Table 5.1: Input data sources for the country-level EAGI formulation

Data	Variable(s) considered	Category	Temporal and spatial resolution	Source
Regulatory Indicators for Sustainable Energy (RISE)	Multiple KPIs (see SI)	Energy sector governance	1 year, country-level	(RISE, 2019)
Transparency International	*Corruption Perceptions*	Politics	1 year, country-level	(Transparency International,

– CPI	*Index (CPI)*			2019)
The Worldwide Governance Indicators (WGI)	Government Effectiveness	Politics	1 year, country-level	(Kaufmann et al., 2011)
Ibrahim Index of African Governance	Sustainable Economic Opportunity	Market	1 year, country-level	(Ibrahim, 2013)
Euler Hermes – Country Risk Reports	Country short and medium term risk	Market	1 year, country-level	(Hermes, 2017)

The indicators are aggregated using a principal component analysis (PCA). PCA is a multivariate statistical method that is used in development research to reduce the number of variables in a dataset and construct composite indices. This technique was first used by Ram (1982) (Ram, 1982) in the construction of a '*physical quality of life index'* and has been used in various fields of development and environmental research since (e.g. (Lai, 2003); (Cahill and Sanchez, 2001); (Khatun, 2009)). The different variables are weighted according to the amount of their variance explained by the first principal component (Booysen, 2002). PCA is only applicable when the variables used are correlated with each other. Rather than a simple mean calculation, PCA gives a more representative score by analyzing correlations between different variables (indicators in this case). The decision to use a PCA in the context of this study is justified by the necessity to come up with a univariate measure summarizing different indicators (the EAGI) that can then be translated into a private discount rate proxy.

Algebraically, a PCA is carried out with the following routine: first, the $d \times d$ covariance matrix of the selected variables for the EAGI is calculated as in Equation 1:

$$cov(X, Y) = \frac{1}{n-1} \sum_{i=1}^{n} (X_i - \bar{x})(Y_i - \bar{y}) \tag{Eq. 5.1}$$

where n is the number of observations in the data (i.e. in our case the number of countries), X_i and Y_i are each couplet of variables at the i^{th} observation, and $\bar{x}$ and $\bar{x}$ are the mean values of each couplet of variables, respectively.

Then, eigenvalues λs (roots of the characteristic equation $\det(A-\lambda I)=0$, where A is the original data matrix and I is an identity matrix) and eigenvectors from the covariance matrix are calculated and sorted by decreasing eigenvalues. Finally, only the k eigenvectors with the largest eigenvalues to form a $d \times k$ dimensional matrix W are retained, i.e. those that bear the most information about the distribution of the data. To conclude, the matrix W is used to transform the initial observation onto the new subspace via the equation $y = W' \times x$, where W' is the transpose of the matrix W. The results of the EAGI calculation are included in the Supplementary Materials.

5.3.2. Implementing the effect of EAGI on the discount rate

Poor governance increases both the perceived and the actual risk of investment in a given project, which can have negative consequences on the profitability of an investment (Jensen, 2003). In Equation 5.2 (source Investopedia.com), the annuity factor AF reflects the present value of future income from a given investment after *i* periods. Here, the discount rate *r* reflects the risk of an investment: the higher the discount rate, the riskier the project, and the lower the AF (which defines the expected return):

$$\mathrm{AF} = \frac{1-(1+\mathrm{r})^{-\mathrm{i}}}{\mathrm{r}}$$

(Eq. 5.2)

Here we aim at describing a similar dynamic in the electrification process – with a particular focus on the decision of private actors to perform capital-intensive investment in electricity access technologies. We have fully integrated the modelling approach for the discount rate in the context of electrification and energy carrier choices introduced in (Reddy, 1996; Train, 1985) into the TIMER model (Dagnachew et al., 2018, 2017; Daioglou et al., 2012). In doing so, we define boundary discount rate values (Figure 5.2A).

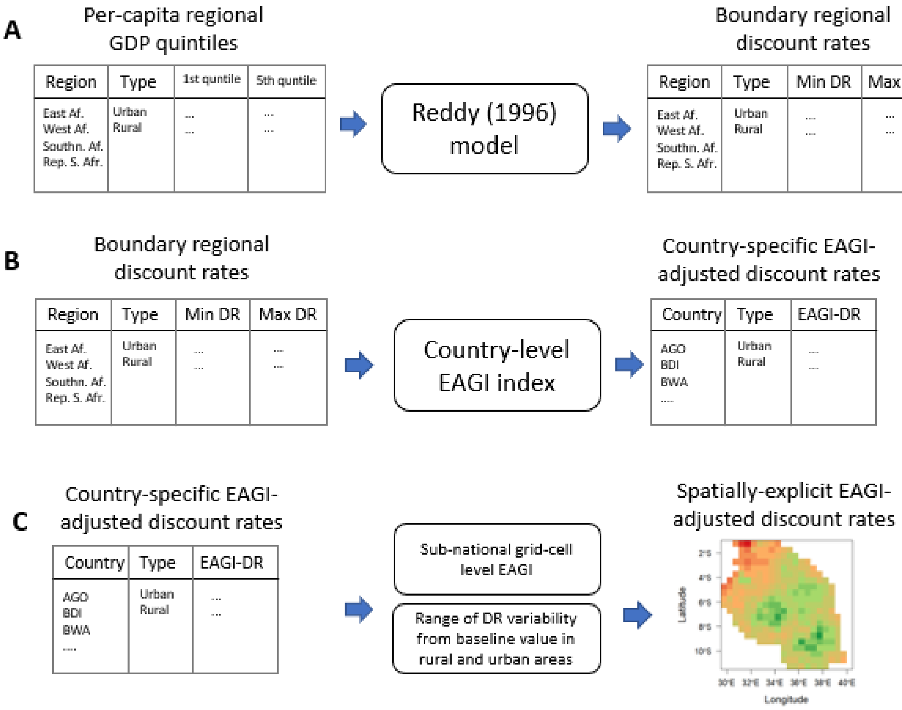

Figure 5.2: Data processing procedure to derive the EAGI-adjusted discount rates. (A) Definition of regional boundary discount rates; (B) Definition of country-specific EAGI-adjusted discount rates; (C) Downscaling of the country-specific EAGI-adjusted discount rates to the grid-cell level EAGI-adjusted discount rates for the case-study countries. Source: author's elaboration.

These values are based on the highest and lowest quintiles of household income, for urban and rural areas separately. In the TIMER model, SSA is divided in to four sub-regions: Western & central Africa, Eastern Africa, the Republic of South Africa, and the rest of southern Africa. The boundary discount rates are identified for each of these sub-regions. These are derived with the following equation:

$$\ln(CDR) = 6.3822 - 0.0082I$$

(Eq. 5.3)

where $\ln(CDR)$ is the natural logarithm of the private discount rate, and I is income (in the original specification of Reddy (1996) expressed in Indian rupees/capita/month as of 1996). Thus, CDR^{max} and CDR^{min} are derived as:

$$CDR^{min/max} = \frac{e^{\left(6.3822 - \frac{0.0082\, I^{q} k}{m}\right)}}{100}$$

(Eq. 5.4)

where I^q are the first and fifth income quintiles of households in each region of SSA, *k=29.756* is a conversion factor from 2011 US dollars (which are the unit of reference for the per-capita average monthly GDP of SSA used in this study) into the original currency[2]. Note that given the lack of availability of income data, we refer to per-capita GDP quintiles. Once boundary discount rate values for each region are derived, the EAGI is linearly normalized (Figure 2B) between this interval (with higher values of the EAGI corresponding to lower values of the discount rate) via the following formula:

$$DR_i^{ur} = (b_r^{ur} - a_r^{ur}) \frac{x_i - \min x}{\max x - \min x} + a_r^{ur}$$

(Eq. 5.5)

where *a* and *b* are the lower and upper discount boundaries for the region to which country *i* belongs, respectively, x is the corresponding EAGI, and the *ur* superscript identifies urban and rural discount rates, respectively. The input numbers for each of the calculation steps are reported in the Supplementary Materials. The result of the modelling yields a set of country and urban-rural heterogeneous discount rates which are linked both to the country-specific regulatory risk and to the region of belonging. These are reported and discussed in Section 5.4.1.

The calculated discount rates differ from the global discount rate of the energy system model (which in IMAGE-TIMER is set at 10%). The latter expresses the cost premium at which society is willing to defer today's benefits in the future, or, equivalently, to accept tomorrow's cost in the present. The EAGI-adjusted discount rates calculated here, on the other hand, refer to the private discount rates in the energy sector of SSA, namely the rate of return that private companies and households are seeking in order to make an investment in the present. Poverty, poor regulatory quality, political instability, and market risk all contribute to increasing the risk of making an investment in the present with returns in the future, and therefore imply the necessity of higher expected return in order to accept that risk.

5.3.3. Introducing within-country heterogeneity in selected case study countries

The methodology introduced mostly focused on a characterisation of the between-country differences in regulatory quality and the relative impact on electricity access investment. This is because generally, the investment

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[2] Based on https://www.historicalstatistics.org/Currencyconverter.html.

environment is determined by national regulation, institutions, and governance that are effective throughout a sovereign country. Yet, it is often the case – and not only in developing countries – that even within a country, there is substantial heterogeneity in the capacity to attract investment. This is a consequence of regional differences in risks. In an attempt to characterise this sub-national differentiation in the context of electricity access investment in SSA, we select four country-studies, namely Nigeria, Tanzania, Uganda, and Malawi, which together host more than 160 million people without access to electricity (IEA et al., 2020) and where highly unequal distribution of electricity access is observed (Falchetta et al., 2020). Given the continental scale of this paper and of the energy investment model considered, we do not implement the sub-national inputs because a geospatial electrification model operated at a higher-resolution (generally < 1 km^2) would be required to appreciate the characterisation of the sub-national heterogeneity in the EAGI discount rate.

We retrieve a set of spatially-explicit data (detailed in Table 5.2) which – consistently with the screened literature presented in Section 5.2 – are deemed strong drivers of the perception of investment risk by private players. These include the PRIO Conflict Site georeferenced dataset on the historical incidence and size of armed conflict in 1989–2008 (Dittrich Hallberg, 2012); the WorldPop poverty maps derived from cell phone and satellite data coupling to household surveys, which report the proportion of people per grid cell living in poverty (Tatem et al., 2013); a measure of accessibility derived from Weiss et al. (2018) for estimating the travel time to the nearest city from any given settlement; and a dataset of excluded ethnic groups in each grid cell (Vogt et al., 2015), which has been shown to be strongly correlated with infrastructure investment in Africa (De Luca et al., 2018). The variables are plotted in Figure 3 for Uganda, one of the four case-study countries selected. Altogether, these spatially-disaggregated factors are deemed effective predictors for the propensity of a private actor to select a given site for infrastructure investment within a country.

Based on a PCA on the spatially-explicit datasets, we operate an adjustment (Figure 5.2C) to the baseline country discount rate estimated via the national EAGI to describe within country-heterogeneity in the potential perceived risk by private investors, and we analyse the results of the electrification analysis with and without the adjustment to understand its implications. The adjustment is within a ±25% range for rural areas and a ±15% range for urban areas, and it follows a grid-cell level PCA and normalisation approach in the same fashion as described in Section 5.3.2. We distinguish between urban and rural areas based on the GHS-SMOD classification. Refer to the Supplementary Materials for a detailed account of the calculation of the sub-national EAGI-adjusted discount rate.

Table 5.2: Input data sources for the within-country case studies

Data	Measured variable(s)	Category	Temporal and spatial resolution	Source
PRIO Conflict Site	Count of armed conflict events; radius of affected area	Political stability	Exact date in 1989–2008 range; 50 km buffer	(Dittrich Hallberg, 2012)
WorldPop poverty maps	% of people living below poverty threshold	Socio-economic indicators	1 year; 1 km	(Tatem et al., 2013)
Travel time to the nearest 250,000+ inhabitants city	Minutes of travel time	Centrailty and accessibility	1 year; 1 km	Major cities data: ESRI; algorithm: Weiss et al. (2018)
GeoEPR	Excluded ethnic groups	Political stability	0.5°	(Vogt et al., 2015)
GHS-SMOD	Urban/rural prevalence	Centrailty and accessibility	5 years; 250 m	(Pesaresi and Freire, 2016)

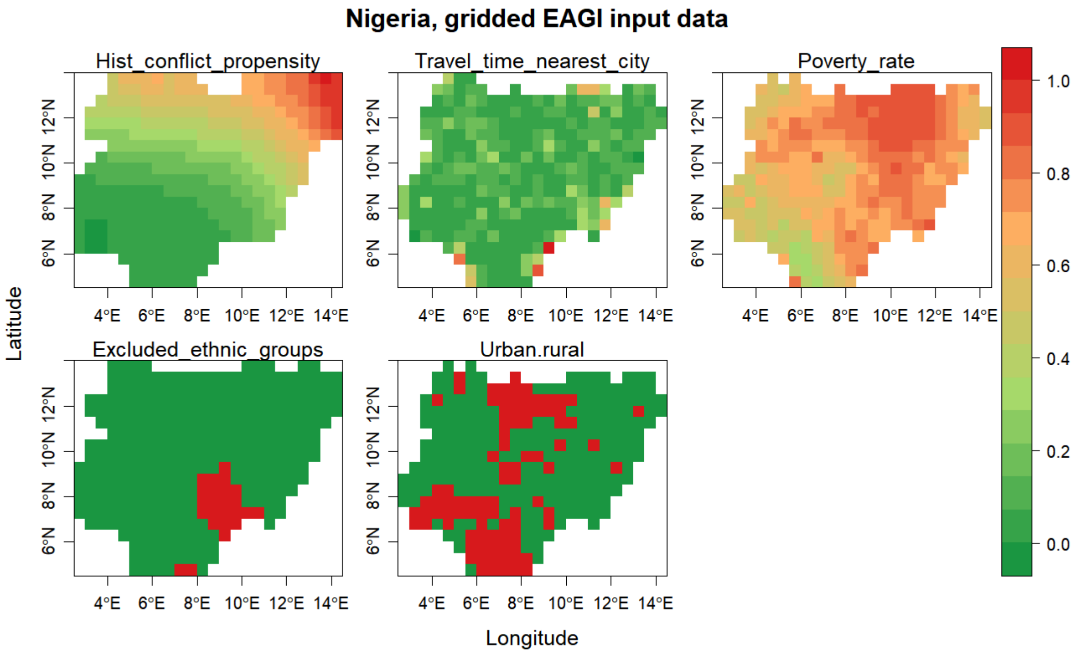


Figure 5.3: Visual representation of selected input data to the sub-national EAGI (normalised range) for Nigeria. From the left to the right: historical propensity to violent conflict; travel time to the nearest 50,000 inhabitants city; fraction of population living in

poverty; density of excluded ethnic groups; prevalent settlement type (1=urban, 0=rural). Source: author's elaboration.

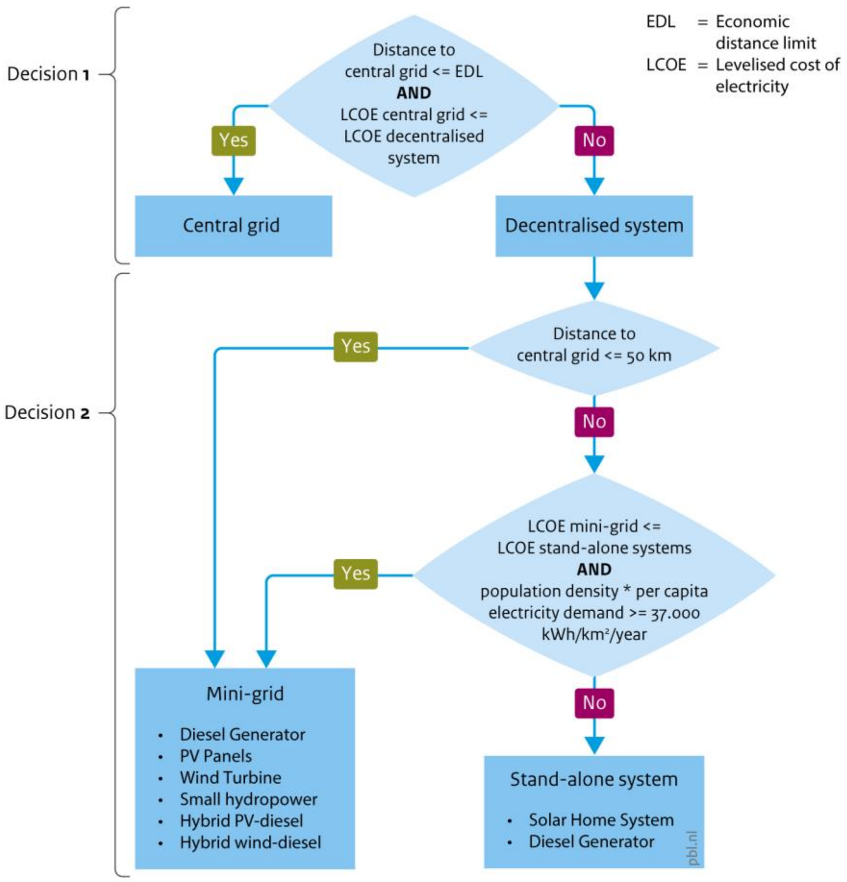
5.3.4. The IMAGE-TIMER model

The *Targets IMage Energy Regional (*TIMER) model is an energy model that forms part of the IMAGE 3.0 framework, developed at PBL Netherlands Environmental Assessment Agency (Stehfest et al., 2014, p. 0). IMAGE 3.0 is an integrated modelling framework that represents interactions between human and natural systems to investigate sustainability issues such as climate change, biodiversity and human well-being. IMAGE is used to analyze large-scale and long-term interactions between human development and the natural environment; hence, it is a data-intensive model. IMAGE has 26 world regions that enables it to capture spatial and multi-scale differences. TIMER is a simulation model that explores long-term trends in demand and supply of different energy carriers, energy access and the possible transition pathways towards low-carbon energy systems. Within the context of IMAGE, TIMER also describes energy-related greenhouse gas emissions (introduced in De Vries et al., 2002).

TIMER model is used in several studies in the past, for instance, to explore residential energy use in developing countries (Van Ruijven et al., 2008), to assess future trends in rural electrification and the associated investment needs in developing countries (van Ruijven, Schers et al. 2012), and to analyze possible future developments of residential energy use in developing regions (Daioglou, van Ruijven et al. 2012). Research carried out by (Dagnachew et al., 2018, 2017) used an extended version of this model to investigate the cost and benefits of various pathways towards universal electricity access in SSA, specifically including several off-grid electrification options. The latter studies were carried out on a 0.5° x 0.5° grid-cell level, allowing results to be aggregated into countries. The SSA Electrification model that forms part of TIMER model is the main instrument of this study. The electrification model incorporates a custom-designed decision tree (see Figure 4) to determine the least-cost electrification option based on the proximity of the grid-cell to an existing power line, the household electricity demand, the population density of the grid-cell, and the cost and availability of local energy resources.

The model provides the least-cost electrification option for each grid-cell in SSA. The input data (population, electricity consumption, grid infrastructure in place, solar/wind/hydro potential, etc.), along with the underlying optimization formulas and full list of parameters used in the model are given in the SI of Dagnachew et al. (2017). The applied model considers different technology options for mini-grid and standalone systems. Standalone systems are isolated systems that can be adopted by individual households and provide up to 250 Wp. These systems do not require transmission and distribution network. Mini-grid systems provide power to a community or small town and comprise low-voltage distribution network. They can be designed to be connected to the national grid with no limit on peak power. Central grid expansion requires high investments in extending the transmission and distribution network and scaling up of generation capacity. The specific characteristics of each technology used in the model, the grid expansion options, and the cost data used can be found in Dagnachew et al. (2017).

Decision tree to determine the lowest-cost electrification system



Source: PBL

Figure 5.4: Decision tree for the IMAGE-TIMER Sub-Saharan Electrification model. Source: Dagnachew et al. (2017)

For the purpose of this study, the model is updated with gridded nighttime light data for electricity access and consumption as developed by (Falchetta et al., 2019). In addition, EAGI-adjusted discount rates are used instead of the standard discount rate used in the model in the previous studies. The model determines the least-cost technology for each grid cell, based on the consumption levels reached in 2030, when universal access in SSA is set to be achieved. The model results visualize and quantify what the cost-optimal technology is for each grid-cell, identifying grid-cells that are viable for off-grid systems, which can be procured by the private sector.

5.3.5. The impact of EAGI-adjusted discount rates on the electrification set-up in the TIMER model

A brief theoretical discussion of how EAGI-adjusted discount rates affect energy-related investment decision is useful for understanding the results of the analysis. In general, the TIMER model selects – at each grid cell – the technology with the lowest levelized cost of electricity (LCOE). The LCOE of technology *i* is defined as:

$$LCOE_i = \frac{\frac{I_{it}}{(1+i)^t} + \sum_{t=1}^{n_i} \frac{OM_{it} + F_{it}}{(1+r)^t}}{\sum_{t=1}^{n_i} \frac{E_t}{(1+r)^t}}$$

(Eq. 5.6)

where, for each technology *i*, I_{it} represents the upfront capital invested (the CAPEX) which is lent at a market interest rate of *i*, OM_t are operation and maintenance costs and F_t are fuel costs (together, the OPEX or running costs), E_t is the electricity generated, *r* is the discount rate (which in a risky investment context is usually >*i*, as *i* might be obtained from less risky capital markets or from development banks), and *n* is the lifetime of the technology in question.

What happens if a consideration of the EAGI implies a *ceteris paribus* higher discount rate *r*? The upfront component (CAPEX) does not depend on the discount rate in the LCOE calculation, while the OPEX does. Therefore, given two technologies *i* and *j* with (discounted) $\frac{CAPEX_i}{OPEX_i} > \frac{CAPEX_j}{OPEX_j}$, a higher discount rate implies that the net present value (NPV) of the OPEX becomes lower and therefore both ratios increase, albeit the ratio of technology j diminishes at a faster rate. This discrepancy is in turn reflected in the LCOE of each technology: while the upfront component I_{it} remains fixed, the OPEX varies with the discount rate.

Given the prevalent cost-structure of central grid expansion (generally grid connections are characterised by lower per-connection CAPEX and higher OPEX) relative to decentralised solutions (higher per-connection CAPEX, lower OPEX), a growing discount rate *r* (i.e. a riskier investment context) tends to imply increasing share of national grid-based electrification. This is the result of the fact that a higher discount rate fosters the deployment of investment at *t = 0* in technologies that have higher running costs throughout their lifetime (fuel and operation and maintenance), since the present value of such future costs becomes comparatively smaller. Thus, in a number of settlements, too high discount rates imply decreasing investment in energy access solutions that have a higher per new connection CAPEX to OPEX ratio (such as solar PV-based decentralised systems) relative to the national grid because lending capital today is relatively more expensive if future costs are more heavily discounted.

5.3.6. Input data and scenarios considered

To explore the pathways for universal access in 2030, we use demographic and economic projections from the Shared Socioeconomic Pathway (SSP) (Riahi et al., 2017). SSPs are a set of alternative futures of societal development used by climate change research community to investigate climate impacts as well as options for mitigation and adaptation. For the purpose of this study, we choose SSP2 scenario since it represents moderate population growth and economic growth, along with acceptance for all energy conversion technologies that do not shift considerably from historical patterns. Historical household electricity demand is calibrated based on (Falchetta et al., 2019). The approach calibrates real historical electricity consumption information based on night-time satellite imagery and other spatially-explicit data. The high-resolution consumption data gives a good indication of current electricity access and consumption levels in SSA and is used to calibrate the model.

Table 5.3 summarizes the scenarios considered in the electrification analysis. We implement a *baseline* scenario based on the original TIMER regional consumer discount rates that only consider household income inequality as discussed in (Daioglou et al. 2012). We then run the model implementing our novel *EAGI-adjusted discount rate scenario*, with country-level urban/rural heterogeneous discount rates. We also test two scenarios simulating the improvement of the EAGI index (as a result of e.g. regulatory and market reform) and thus lowering the discount rates. The *moderate case* assumes 25% improvement in rural areas and 50% improvement in urban areas, while the *substantial* case displays 75% improvement in urban areas and 50% improvement in rural areas from the current EAGI values.

Table 5.3: Table of the scenarios considered in the electrification analysis

Scenario	Discount rates	EAGI
Baseline	TIMER baseline (regional)	-
Baseline-EAGI	EAGI-adjusted	Baseline
Moderate improvement in	EAGI-adjusted	25% improvement in rural areas; 50% improvement in

EAGI		urban areas
Substantial improvement in EAGI	EAGI-adjusted	75% improvement in urban areas; 50% improvement in rural areas

5.4. Results

5.4.1. EAGI and implicit discount rates

Figure 5.5 summarizes the calculated EAGI-adjusted discount rates which are considered in the electrification analysis. The underlying numbers are also reported in a tabular form in the Supplementary Materials. The results suggest that there is a significant range of variability across countries, with EAGI-adjusted discount rates of less than 20% in urban areas of Botswana up to rates of more than 80% in rural Somalia. Investing in urban areas is always less risky (i.e. costly) than in rural areas, although the difference decreases as discount rates increase. Among the countries with the lowest EAGI-adjusted discount rates are Botswana, Rwanda, Namibia, Kenya, Tanzania, Ghana, South Africa, and Ethiopia, which all share urban and rural EAGIs lower than 40% and 50%, respectively. Not by chance, according to the recent national statistics reported in (IEA et al., 2020), these countries are among those with the steepest growth in electrification levels since 2010. Conversely, the risk premium is deemed very high in Somalia, South Sudan, Chad, the Central African Republic, Eritrea or the Republic of the Congo.

Figure 5.5: Country-level EAGI-adjusted private discount rates in rural and urban areas. The x-axis describes EAGI-adjusted private discount rates; colours report the TIMER region of belonging of each country; the symbol size describes PPP per-capita GDP; the shape of the symbol distinguishes between rural and urban areas. Source: author's calculations.

As expected, most of these countries have some of the lowest-ranking figures for both electricity access levels and their growth rates. Yet, notable exceptions exist, such as for the case of the Republic of the Congo, where a risky profile driven by poor performance in the energy access regulation and corruption indicators has not prevented the country from experiencing a significant growth in electricity access. This shows that there is not necessarily a linear relationship between private discount rates and electricity access progress. One reason for this is that public investment in infrastructure is sometimes not well balanced into market mechanisms and can be driven by political objectives rather than market considerations. This is mostly the case for public-owned and controlled infrastructure, such as expansion of the national grid. Conversely, the market for off-grid electrification is dominated by private players which are more responsive to economic considerations. Our paper is mainly looking at the latter players, namely at the challenges faced by companies in their electricity access investment decisions.

As detailed in Figure 5.6, we fine-tune our methodology in four selected case-study countries where we consider sub-national heterogeneity in the EAGI-adjusted discount rates. The results provide a more detailed layer of information on how the potential sources of risk for investors are located within a country. Not only the maps make the urban-rural divide evident, but also, they put considerable weight on remoteness, poverty, and the historical conflict record and ethnical exclusion.

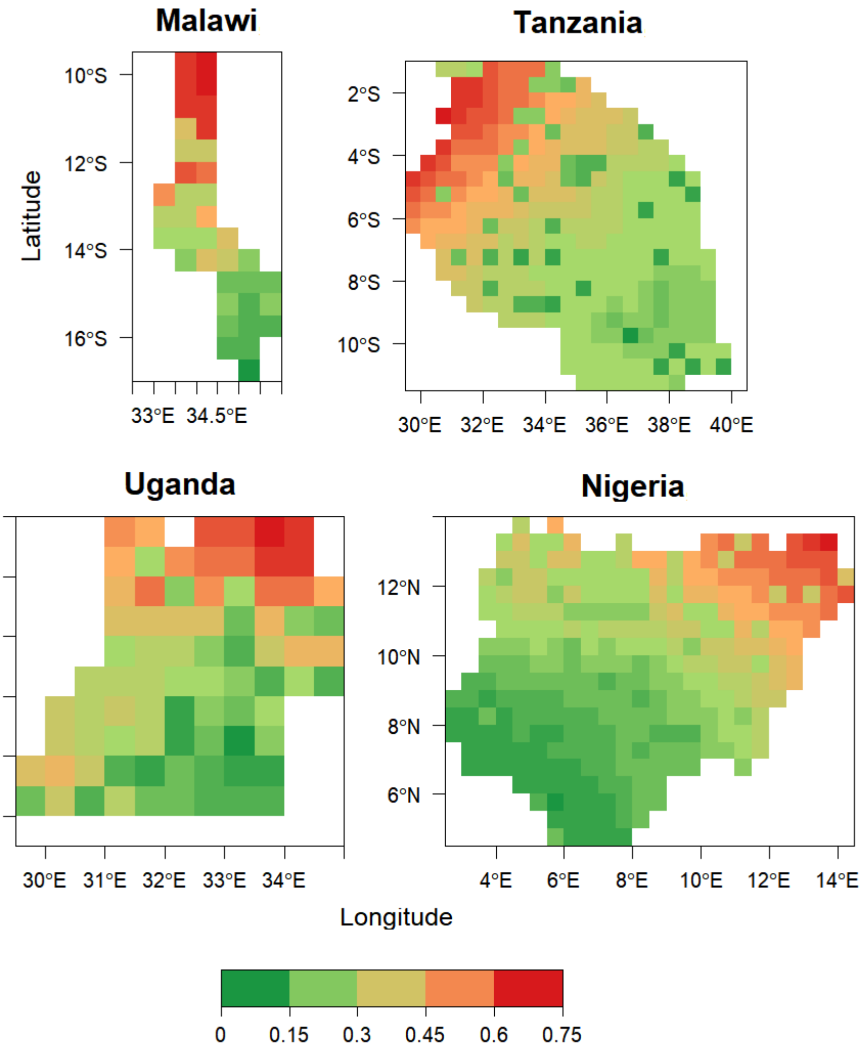


Figure 5.6: Sub-national results for the estimated private discount rates (based on the EAGI and adjusted via sub-national covariates) in the selected case-study countries. Source: author's calculations.

5.4.2. Optimal technology mix and Investment requirements

Figure 5.7 presents the results of the electrification analysis in terms of the optimal share of electrification systems among households in 2030. As discussed in Section 5.3.6, it compares two main scenarios: a *baseline* (calibrated on historical electrification progress and investment) and a *universal electricity access* variant (imposing universal electricity access by 2030). Each scenario is simulated both with a default discount rate configuration (*regional DR*) and with country-specific, urban-rural heterogeneous DRs (*EAGI-adjusted DR*).

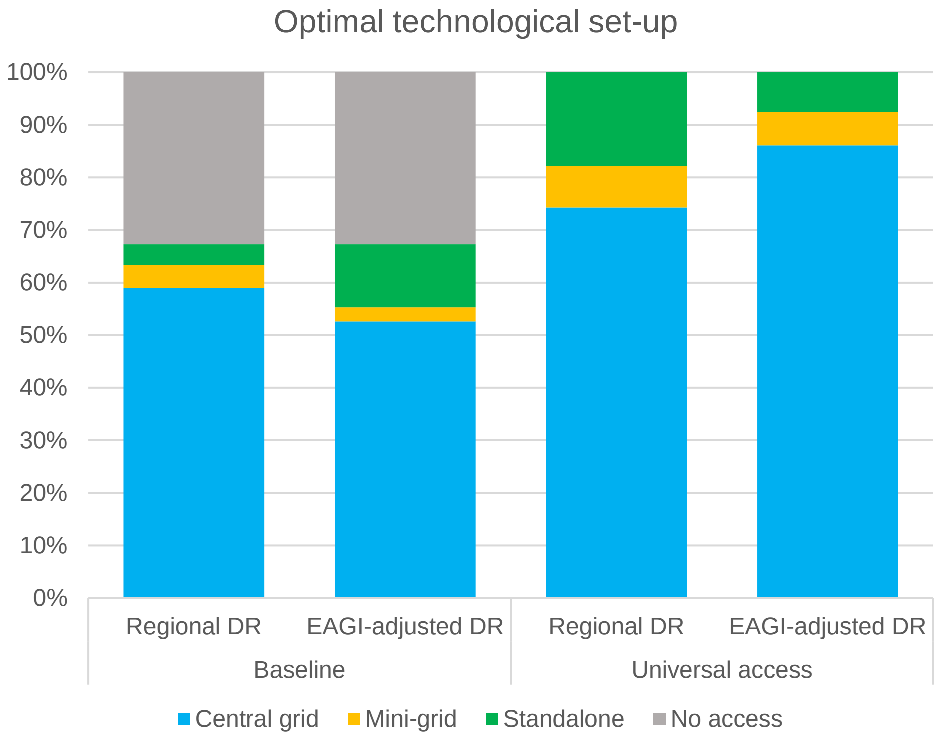


Figure 5.7: Results over the optimal technology mix in baseline and EAGI-adjusted scenarios. Source: author's calculations.

The results show that in the *baseline scenario* standalone energy access systems (e.g. diesel gen-sets and solar home systems) display a comparatively higher penetration relative to the central grid extension when running an analysis based on EAGI-adjusted DRs. This is because the baseline scenario implies the persistence of electricity access gaps in 2030 precisely in areas with high discount rates (where historically electricity access progress has lagged behind). Conversely, areas gaining electricity access are likely to display better governance performance and therefore are more attractive for private developers of decentralised systems, resulting in a switch from central grid access to standalone system access. The more detailed spatial distribution of risk increases the proportion of sites that can be successfully electrified by private energy access solutions providers.

In the *universal electricity access scenario* (where – by design – even areas with poor governance receive electricity access), the heterogeneity in the characterisation of risk through the EAGI-adjusted DRs emerges as a relative aversion to standalone and mini-grid systems. The main reason behind this finding is that in general, these energy access solutions (and in particular solar PV-based decentralised systems) have a higher per new connection CAPEX to OPEX ratio (capital upfront costs to operational costs, i.e. fuels, maintenance…) relative to the national grid. Thus, a higher discount rate (i.e. a higher cost of capital) tends to favour systems with comparatively lower CAPEX to OPEX ratios (and therefore LCOEs), as lending capital today is expensive and future costs are more heavily discounted. Coincidentally, areas with the largest energy access deficit (i.e. which remain without electricity access in the *baseline variant*) are likely areas with poorer performance of the EAGI index. Thus, a more detailed characterisation of risk sheds light on the intrinsic difficulty of decentralised systems to have a substantial role under a risky environment for private investors. In fact, in high risk countries, access through the central grid does not guarantee access. It just shows that the private sector is reluctant to invest in decentralized systems leaving the central grid as the least expensive solution to expanding access.

Figure 5.8 reports the results of the same scenarios in terms of the system-specific yearly average investment requirements. The annual investment gap under standard DR characterisation is ~30 bn, which is indeed similar to (Dagnachew et al., 2017). Applying the EAGI-adjusted discount rates leads to an additional investment gap of 25 bn/year. This is the result of different trends: on the one hand, investment in all access systems becomes *ceteris paribus* more costly. In addition, the technological shift observed in Figure5. 7 – namely the crowding out from decentralised systems – implies the need to expand the central grid even in areas where it is very costly to do so (because of remoteness, low demand density, and risk encapsulated in the EAGI).

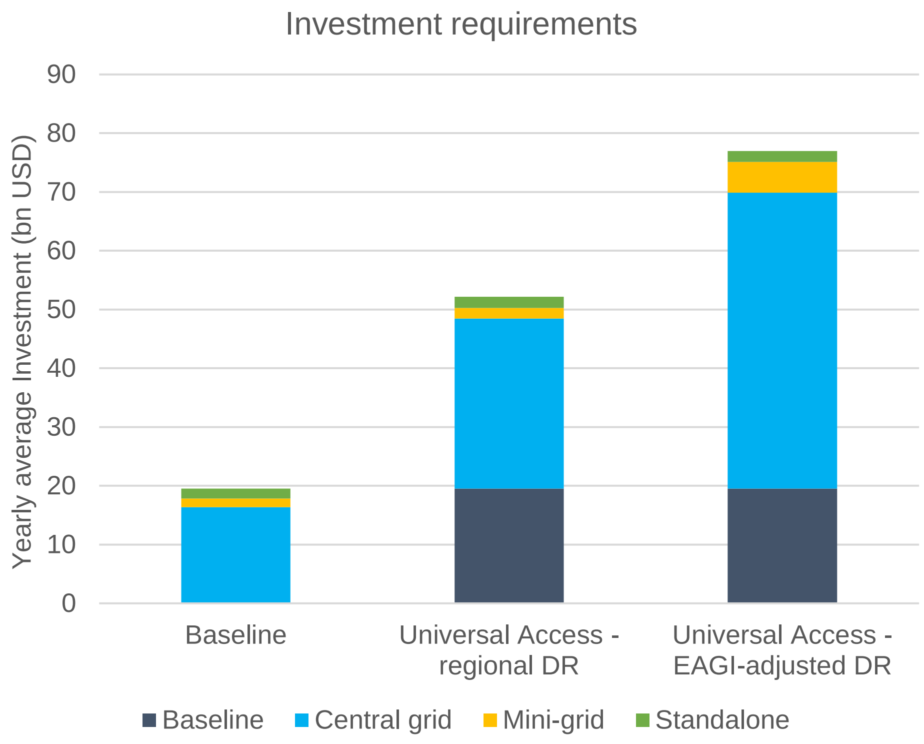
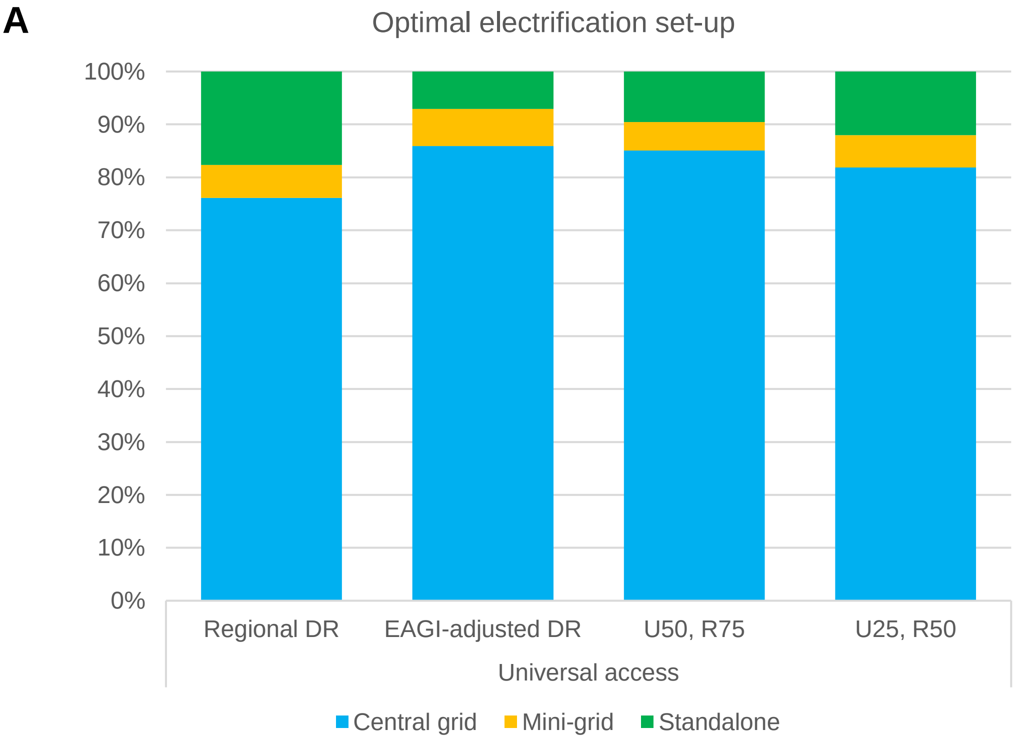


Figure 5.8: Results over the electrification investment requirements in baseline and EAGI-adjusted scenarios. Source: author's calculations.

5.4.3. Simulating improvements in the EAGI

To evaluate the sensitivity of the results, we explore the significance of improvements in the EAGI index as a result of political and economic reform. The *moderate case* assumes 25% improvement in rural areas (R) and 50% improvement in urban areas (U), while the *substantial* case displays 75% improvement in urban areas and 50% improvement in rural areas from the current EAGI values.

Figures 5.9A-B show the results for respectively the share of new connections and the investment requirements. As expected, gradually increasing regulatory quality leads to growing shares of decentralised (and mainly standalone) systems and lower investment requirements, due to both structural capital cost reduction and to CAPEX/OPEX ratio variations which in turn reshape the optimal energy access technology set-up. Yet, mini-grids and standalone systems remain limited in terms of the number of new connections. Even in the *substantial* EAGI improvement case, their penetration is altogether <20%.



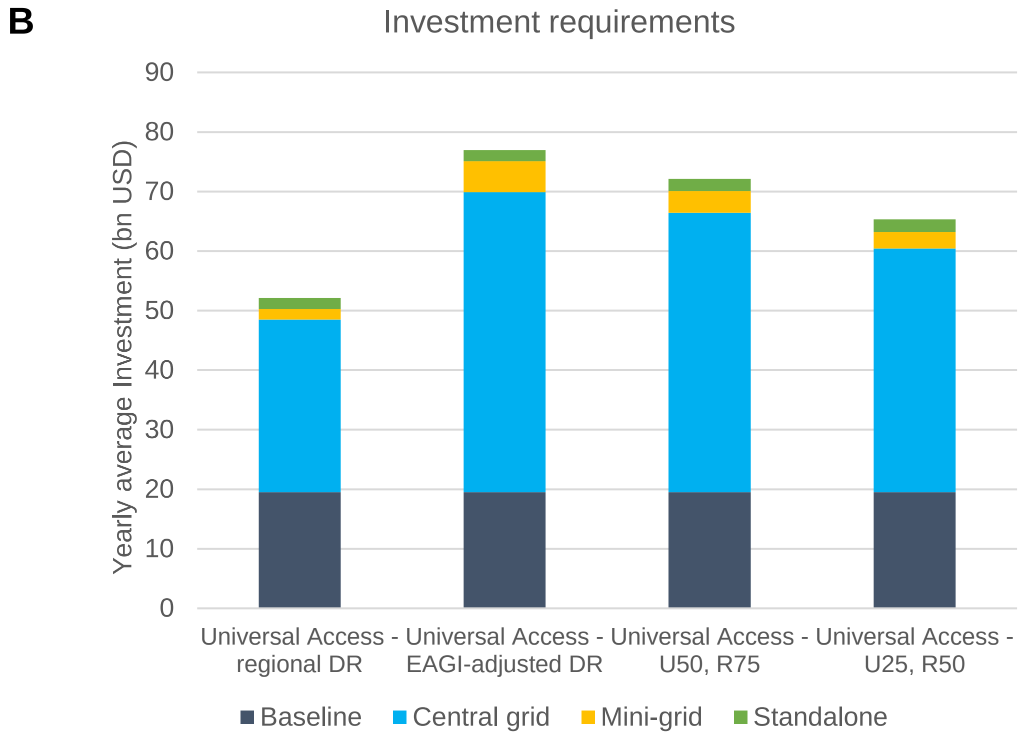


Figure 5.9: Results of the sensitivity analysis across scenarios. (A) Sensitivity of the optimal electrification technology set-up by the share of new connections; (B) Sensitivity of the electrification investment requirements, by electrification technology. Source: author's calculations.

5.4.4. Results summary

Together, the results from the TIMER model suggest that the uptake of decentralised systems for achieving universal energy access requires governance reform to lower the discount rate. In the lack of such institutional transformations, the key risk incurred by countries with electrification deficit is that areas which would be cost-optimally served by decentralised systems such as mini-grids and standalone systems do not get technologies installed because of the high DRs pushing away private investors. At the same time, the government would likely face financial barriers in connecting those areas to the national grid because of their distance to the existing grid or the low local demand which would not allow recouping the investment.

In addition, the results presented in this section are likely to vary with the consideration of different demand targets and technology-specific cost variation. Yet, these additional sensitivity runs are beyond the scope of this paper. The results show that varying perceived risk have a *ceteris paribus* significance for electricity access planning. The most prominent effect is on the total investment requirements, but a significant effect is also observed in the optimal technology mix.

5.5. Discussion

Recent literature based on stakeholder interviews and institutional analysis (Dagnachew et al., 2020; Simone and Bazilian, 2019) has discussed how energy resource abundance is not a sufficient criterion to ensure elimination of energy poverty because of the existence of a variety of barriers. These barriers include market failures (e.g. due to a bundled, highly centralised energy sector) such as a lack of competition and high transaction costs; market distortions such as regressive subsidies hampering investment decisions; economic and financial barriers driven by risk perceptions for private system developers as a result of a multitude of causes (political, regulatory, monetary, conflict risks).

Building on this qualitative understanding of the main challenges to universal electrification in SSA, our paper has developed and implemented a methodology to quantitatively and explicitly account for the role of regulatory, political, and market risk factors in electricity access modelling. This analysis led us to a key finding: the results of the electricity supply analysis change substantially compared to a pure, conventional techno-economic assessment. Namely, accounting for different risk factors crowds out investment in decentralised systems which – compared to a conventional analysis – shrink their share on new connections when pursuing a universal electricity access policy. This contraction is the result of risks increasing private discount rates, and therefore the willingness of private actors to invest in decentralised energy access systems (which have higher CAPEX-to-OPEX ratios).

With regards to the interpretation of the modelling exercise results, it is important to note that the *universal electrification scenarios* quantify the technological and investment requirements to achieve SDG 7.1.1 under a set of given conditions – including the current risk –, but it does not provide any specific evidence that those outcomes identified as optimal will actually materialize. What does this mean? For instance, the significant growth in the share of connections via central grid expansion in the EAGI-adjusted DRs variants (and therefore the growth in the overall investment requirements) casts doubts on the actual possibility of deploying large-scale public infrastructure with considerable governmental expenditure to reach sparse communities with low demand loads. These findings are in agreement with the results from the stakeholder interviews of Dagnachew et al., (2020), who claim that *‘achieving universal access to electricity through the integration of off-grid systems requires innovative revenue schemes, financial and fiscal incentives and elimination of market distortions’*.

How can these barriers be overcome, and decentralised systems realise the potential that they are claimed to have (Dagnachew et al., 2017; IEA, 2019)?

The keyword here is reform. Reform of the regulation of the energy sector to enable a competitive and attractive environment for private and foreign investors; reform of the bureaucracy mechanisms to ensure accountability, efficacy and the reduction of corruption and clientelism among decision makers; market reform, to ensure the reduction of frictions in the labour and capital markets; fiscal reform, to ensure tariffs (including energy taxation) are progressive and development investments, such as energy access, meet favourable conditions; monetary policy aimed at ensuring the minimisation of exchange rate fluctuations which might otherwise lead to fast appreciation or depreciation of the currency, with potential losses for foreign investors. Regulatory reform is not solely a task for governments in SSA, as policies implemented in countries of the Global North (where most donors and investors are based) also have a relevant weight. For instance, competitive subsidies such as results-based financing from developed economies can support private companies in SSA to invest.

In the meantime, private companies in the energy access sector are seeking strategies to minimise their operational risk and maximise value to be able to invest in new infrastructure even when facing relatively high discount rates. Pay-as-you-go (PAYG) schemes among communities served by decentralised energy access solutions are gaining growing relevance, in particular when combined with ‘over the counter’ electrification products such as plug-and-play solar kits and solar home systems. From the companies’ perspective, these innovative models can be seen as a hedging investment. PAYG business models in fact allow companies to set high interest rates – and thus make profit from *quasi* microfinancing investments – while at the same time lifting poor communities from the burden of simply unsustainable high upfront costs such as national grid connection charges or standalone systems purchase.

While central grid infrastructure investment has also recently received the attention of large-scale foreign (in most cases Chinese, e.g. GEIDCO) corporations in the context of pan-sectoral market development operations such as the prospect of a global grid, these developments are likely to be strongly biased towards certain regions and neglect others, because they are not driven by explicit energy access objectives. Contrarily, these CAPEX-intensive investments target large demand hotspots such as industrial areas or metropolitan cities because they have the specific objective of ensuring the grid natural monopoly and then be able to import power from abroad.

To conclude, it must be remarked that the assumptions made in this application of the model inevitably result in simplification. The main limitation include (i) the data-availability dependent selection of the factors included in the EAGI; (ii) the simple mechanism linking the EAGI to the discount rates; (iii) the intrinsic limitations of the TIMER electrification model, detailed in (Dagnachew et al., 2017); (iv) the lack of consideration of investors peering dynamics – found to be important in the literature on investment in developing countries and yet challenging to implement due to the lack of granular historical data on investment flows in the energy access sector. Future research should aim at tackling these key limitations to evaluate the robustness of our results over the sensitivity of electrification investment to different sources of investment risk.

5.6. Conclusions

We have shown that regulatory quality and governance can have a significant impact on the optimal investment strategy for private companies involved in energy infrastructure in developing countries. Our results are directly relevant to policymakers, because they show that targeting specific domestic issues by means of better governance and regulation can increase incentives to attract more private-sector investment. This diminishes the required investments by the central government to expand the central grid in the short run.

With poor regulation, it is likely that the expansion of the national grid is the only way to bring electricity to communities that are currently without access, because decentralised systems developers do not have the sufficient economic incentive to develop a decentralised energy access solution. In the model, this is reflected by the fact that operational costs become less relevant and capital costs more relevant for energy investment decisions with higher discount rates. Investors therefore tend to prefer systems with lower capital costs to operational costs ratios. Since decentralised systems have comparatively higher upfront costs per new electricity connection than extending the central grid, their development becomes less and less attractive under higher discount rates. In turn, under poor regulatory quality and therefore energy sector governance, the government is itself also less likely to invest in the grid, locking the country into an energy poverty trap and reinforcing electricity access inequality (Falchetta et al., 2020).

We recommend future research assessing electrification to give more prominent role to governance, regulation, and risk dynamics. Assessing what is the least-cost technology is not enough to have this installed if there are no market conditions to attract players that can actually put the infrastructure into place on a large scale. This is crucial to achieve SDG 7.1.1 timely.

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6. Hydropower dependency and climate change in sub-Saharan Africa: a nexus framework and evidence-based review

6.1. Introduction

In sub-Saharan Africa[3] (SSA), the installed hydropower capacity stands at 27 GW (39% of the total), with additional 15 GW planned or under construction (International Hydropower Association, 2018). In 2016, hydropower generation stood at 98.6 TWh (US EIA, 2017). A gross technical untapped potential of 7.7 PWh/year (Hoes et al., 2017) has been estimated, of which between 1.4 (below a cost of $0.10/kWh) (Gernaat et al., 2017) and 2.9 (below a cost of $0.09/kWh) PWh/year (Zhou et al., 2015) remaining and techno-economically feasible. The (IEA, 2017) forecasts that hydropower capacity in SSA will increase at a rate of 6% per year during the 2020s (and thus be the fastest-growing technology in terms of capacity additions), reaching 95 GW by 2040 (IEA, 2014). Currently, total generation capacity in the continent amounts to around 70 GW (Figure 6.1a), although around 25% is currently unavailable because of obsolete plants and poor maintenance (Findt et al., 2014). In many countries - and chiefly in Central and East Africa - the electricity generation mix is weakly diversified (Figure 6.1b), with hydropower accounting for a large part of total generation and few back-up options available. Together, hydropower-dependent countries - defined as countries where hydropower represents more than 50% of total electricity generation - host 45% of the total SSA population, or 160 million grid-connected users.

In the last decades (in particular during the wet season in unimodal rainfall climates, where rain falls only during one period per year) prolonged droughts have resulted in severe power crises in several hydropower-dependent countries (including for instance, in Kenya, Tanzania, Ghana, Zimbabwe and Zambia during the 2015-16 El Niño period, characterized by oceanic and atmospheric shifts in the Pacific Ocean which affect weather and climate across the tropics, and in Malawi in 2017), with frequent outages, power rationing (M. T. van Vliet et al., 2016), adverse business experience (Gannon et al., 2018) and switching to emergency (and costlier) IPP (independent power producer)-provided diesel-fired generators (Karekezi et al., 2012). Water availability issues represent a growing source of risk in different areas, also due to an increasing

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[3] Throughout this essay, excluding South Africa.

competition between water use for power generation, irrigation, and municipal water supply (Kling et al., 2014; Zeng et al., 2017).

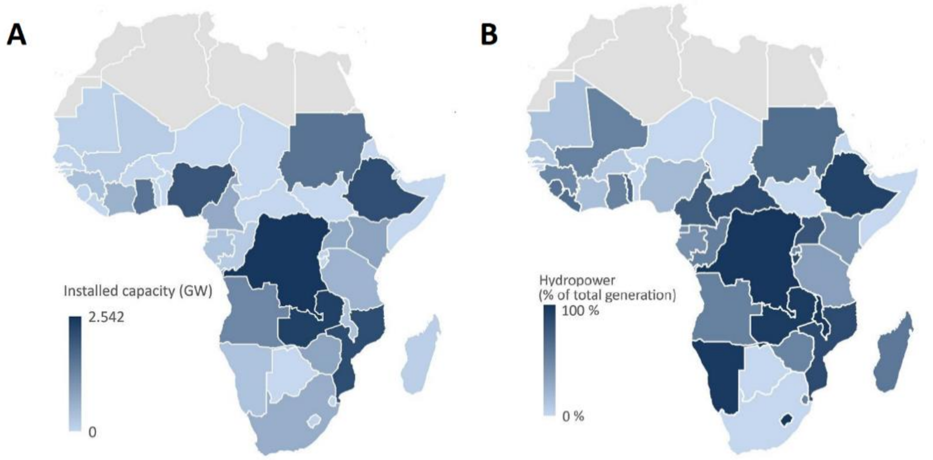

Figure 6.1: Maps of sub-Saharan Africa representing (a) the total installed hydropower capacity in 2016 and (b) the share of hydropower over the total power generated domestically in 2016. Data source: (US EIA, 2017). Source: author's calculations.

A vivid debate is taking place in the academic literature and in decision-making spheres on whether and how in the coming years anthropogenic climate change - and thus changing precipitation and evaporation patterns - will affect hydropower potential and reliability, next to additional demographic and socioeconomic stressors. A number of studies have been carried out to assess the impact of past extreme events (including both droughts and floods) on hydropower at different geographical scales in SSA (Gannon et al., 2018; Kabo-Bah et al., 2016; Loisulie, 2010; Stanzel et al., 2018; Uamusse et al., 2017) and to model projections for future trends in water availability and hydropower output (Cervigni et al., 2015; Conway et al., 2017; Sridharan et al., 2019; Turner et al., 2017a; M. T. H. van Vliet et al., 2016). However, there appears to be a lack of a systematic review paper focusing on the specific issue of hydropower dependency in SSA, building on a robust theoretical framework, and analysing relevant data to account for the current capacity expansion plans and for different climate change scenarios.

6.1.1. Review approach

To address the gap, this paper adopts an analytic approach to provide a state of-the-art picture of the issue of hydropower dependency across SSA under the projected impacts of climate change. The review is carried out in three steps, as described in Figure 6.2a. First, the relevant literature is collected and screened.

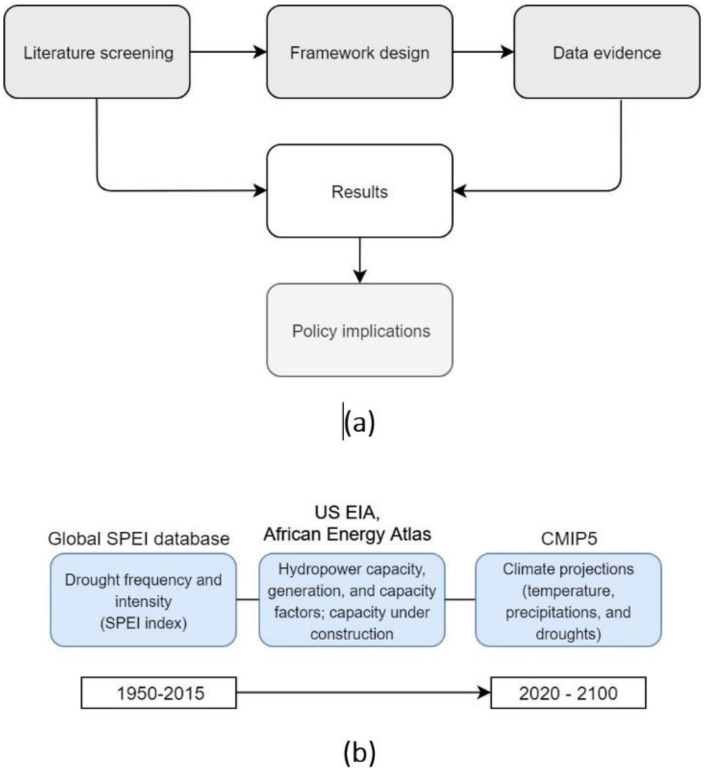

Figure 6.2: (a) Schematic of the review approach. An initial literature screening underpins the design and discussion of a framework of relationships for the climate-water-energy nexus considered. Data evidence supports the findings of the literature reviewed and addresses conclusions and policy implications. (b) Schematic of the data evidence section. Drought data is used to assess the trends in frequency and intensity of drought events recorded over nine major river basins throughout the twentieth century. Hydropower data is analysed to assess past trends and current pathways of hydropower dependency and diversification. CMIP5 climate projections are reported to discuss implications for the coming decades. Source: author's elaboration.

An explicit decision to assess studies focusing on the relationship between climate change and hydropower in SSA, rather than water resources in general or in other specific contexts is made. At the same time, the review adopts a forward-looking perspective on the status quo and on projected future pathways and impacts, rather than systematically reviewing past drought-induced disruptions. Subsequently, a framework to highlight the range of relationship linking hydropower generation, water availability, GHG (greenhouse gas) emissions, climate impact, and energy system development is derived and represented. Specific implications for the three main types of hydropower plants (run-of-river, reservoir and pumped-storage) are discussed. Thirdly, based on a selected number of aspects of the conceptual framework (focusing on hydropower, droughts, and climate change) and on the literature screening, the review is supported by data evidence (Figure 6.2b). Data sources include the

US IEA International Energy Statistics database (US EIA, 2017), the SPEI (Standardized Precipitation-Evaporation Index) global droughts database (Beguería and Vicente-Serrano, 2017), the African Energy Atlas 2017-18 power infrastructure data (Cross-border Information, 2017), and CMIP5 (Coupled Model Intercomparison Project - phase 5) climate projections (Taylor et al., 2012). Lastly, insights from the three analytical steps are presented in the discussion section, where the key implications of the review are highlighted to the research community, the private sector, and public decision makers.

The remainder of the paper is structured as follows: in Section 2, a theoretical framework of the interlinkages between the power sector, the climate system, and the broader economy is presented, with specific focus on hydropower generation and water availability. Sections 3 and 4 report the results of the literature review process and of the data evidence on (i) the historical evolution of hydropower installed capacity, generation and capacity factors, (ii) current and planned generation capacity additions, (iii) the trends in the frequency and intensity of drought events, and (iv) future climate change projections. Section 5 discusses the most relevant findings and the key implications for energy-water systems planners and researchers. Section 6 concludes the paper.

6.2. Theoretical framework

Figure 6.3a represents the diagram of relationships derived from the initial literature screening. This is aimed at highlighting the key elements of the climate-water-energy nexus (Frumhoff et al., 2015) which is taken as a reference throughout the review. These include drivers, impacts, their linkages, and feedbacks. The focus is put on the power sector, and the framework is designed so as to be particularly suitable to analyse the case of SSA.

The following considerations characterise the conceptualised relationships:

(i) Demand for power is strongly associated with economic growth. Despite the direction of the causal link between the two being a controversial question in the literature (Dlamini et al., 2016; Eggoh et al., 2011; Inglesi-Lotz and Pouris, 2016, p.; Iyke, 2015; Louw et al., 2008; Wolde-Rufael, 2006), with some studies pointing at the simultaneous causality hypothesis, and others suggesting a mono-directional or a less clear link, it is acknowledged that a strong correlation exists. Other drivers include population, urbanisation, and employment levels (Ubani, 2013). Power demand contributes to determining energy policy, which drives supply-side decisions.

(ii) Power can be generated in several ways, and chiefly: (i) with thermal-generation, i.e. fossil fuel-fired plants and nuclear units, but also geothermal and biomass power generation, or CSP (concentrated solar power); (ii) mechanically, from kinetic energy, including hydropower facilities (hydropower plants and pumped storage), wind turbines, or tidal energy; (iii) through solar photovoltaic (PV) units. Thermal generation from fossil fuels results in multiple externalities, as it is associated with greenhouse gas emissions and (together with nuclear energy) it implies the consumption of substantial volumes of water for cooling purposes (albeit consumption largely depends on the technology installed, Macknick et al., 2012).

(iii) GHG emissions from fossil fuels combustion contribute to climate change (Pachauri et al., 2014), raising mean temperatures and affecting precipitation and evaporation patterns. Modelling studies show that climate change could exert substantial impacts on water availability in SSA (Faramarzi et al., 2013), although large uncertainty exists regarding the magnitude of these changes in different regions. In turn, climate change may impact virtually every sector of the economy, affecting productivity, energy demand, and infrastructure (through increasing the likelihood of extreme events). The adaptive capacity of each country determines the effects of such linkages.

(iv) Water availability is key for many economic sectors, and primarily for agriculture. This is of great importance to SSA, where agriculture accounted for 17.5% of value added to GDP (gross domestic product) in 2016 (World Bank, 2018), with the figure standing at more than 30% in several countries largely reliant on subsistence agriculture. Hence, increased water pressure can have substantial impacts on food security and on economic growth as a whole.

(v) Hydropower generation is tightly linked to water availability, since turbines require the streaming of large volumes of water to generate power. At the same time, artificial reservoirs can affect both the seasonal flow (releasing more water during the dry season and holding it back during the wet season), and the overall flow because of increased evaporation (Bakken et al., 2013; Mekonnen and Hoekstra, 2012). Again, this depends on the hydrological basin in question, the type of hydropower facility, and the other prevalent water uses in the region. Moreover, an important upstream-downstream coordination dimension also exists and is highly relevant to the case of SSA, in particular for transboundary water resources management (Namara and Giordano, 2017).

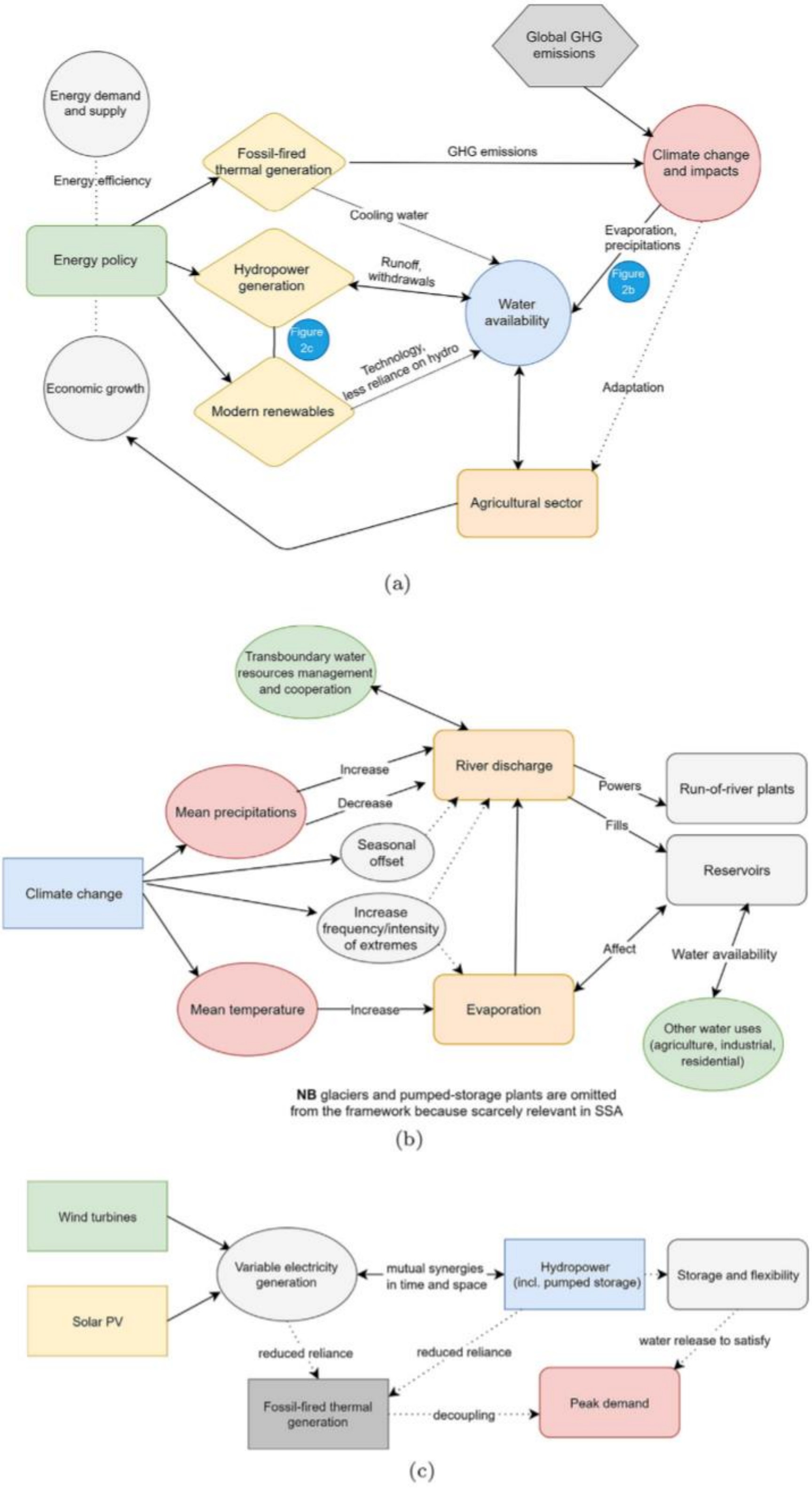

Figure 6.3: (a) The climate-water-energy nexus framework considered in this review. Solid lines express direct drivers and impact, while dashed lines describe indirect relationships, where mediating factors play a role. Arrows express whether effects are uni- or bidirectional. (b) Schematic of the key channels of climate change impact on

hydropower schemes reliability. (c) Example framework of greenhouse gas emissions mitigation via VRE-hydropower complementarity.

(vi) Non-hydro RE (renewable energy) sources can have the benefits of generating power without contributing to greenhouse gas emissions, while affecting the supply of water to a much lesser extent and of reducing greenhouse gas emissions. They can also serve to extract water (e.g. via water pumping) and mitigate competition over reservoirs in dry areas, and thus help to serve irrigation needs in the agricultural sector. Furthermore, if properly planned, hydropower can work in tight complementarity with intermittent RE such as solar and wind, serving as a technology for energy storage (as reservoir water) to accommodate demand peaks and seasonality (Barasa et al., 2018; Francois et al., 2014; Rogeau et al., 2017; Sterl et al., 2019, 2018), and not solely as a source of baseload power (see also Fig. 6.3c) later.

(vii) Finally, the treatment and distribution of water can require a considerable quantity of energy (Opperman et al., 2015).

Figure 6.3b expands the framework of Figure 6.3a to explore the interdependencies between climate, water, and hydropower generation. In particular, it suggests that:

(i) Hydropower generates electricity via falling water hitting a turbine connected to a generator. The power output is a function of both the flow impacting the turbine and the hydraulic head. As a result, changes in hydro-climate may affect hydropower generation (Lumbroso et al., 2015). The channels through which climate change affects hydropower capacity and effective output include alterations in the gross stream flow, shifts in the seasonality of flows and a greater variability (including flood and drought extremes), increased evaporation from reservoir lakes, but also changes in sediment fluxes (World Commission on Dams, 2000).

(ii) Anthropogenic climate change determines changes in the long-term mean of hydroclimatic parameters - chiefly temperature and precipitative fluxes , as well as the seasonal shifts and the probability and intensity of extremes (droughts and floods) (Pachauri et al., 2014).

(iii) The extent to which such changes affect power generation and the actual capacity factor of hydropower plants depends on multiple factors, including: the direction and magnitude of the change; the type of dam in question; and for the case of reservoirs, the features and size of reservoir; among multipurpose dams (which are usually also the largest), the withdrawal from concurrent uses and thus the use of shared water resources in the region by the agricultural sector, the industry, and residential areas (Lee et al., 2009); and the transboundary basin management (Conway et al., 2015). *Source: author's elaboration.*

(iv) Hydropower includes plants of three main categories: RoR (run-of-river), reservoir-based, and pumped storage plants. Plants however often operate intermittently as RoR and reservoir-based. For example, plants with multiyear reservoir lake capacity can buffer inflow across multiple years, whereas plants with within-a-year capacity can only do it for several months before they would overflow. The first type utilizes the river's flow to produce electricity without blocking water upstream; the second partially stops the flow of a river with a dam and floods an area upstream to create a reservoir lake. Reservoirs are capable of buffering fluctuations in flow over longer time periods, and hydropower plants with reservoirs can thus be well-suited for providing base power (relatively constant output) and peak power (increased power output at particular moments). Depending on the vulnerability of the plant's technical equipment (such as the turbine equipment) to the impacts of variable discharge rates, it might be decided to operate only for baseload provision. Conversely, depending on the vulnerability of downstream ecosystem services to the impacts of constant discharge rates, it might be decided to operate plants mostly as run-of-river facilities (Liersch et al., 2019). As of 2019, no pumped-storage facilities are in operation throughout SSA. Four schemes are operating in South Africa in conjunction with the constant generation. These facilities serve to meet the intra-daily variations in the electricity demand, but can also be used to store generation potential from other variable RE (such as solar and wind) during moments of overproduction from the latter, reducing curtailment rates.

(v) Considerations related to the cooperative (or competitive) dynamics of water resources management are necessary. Transboundary river basins cover 62% of the total surface of Africa, and water availability (and water infrastructure management) downstream is largely affected by political and infrastructural choices upstream (Grey et al., 2016). Cooperative governance can reduce water conflicts, increase efficiency in resource use including hydropower output - and create economic value by internalizing externalities stemming from a lack of coordination, and therefore boost investment and financing of shared water infrastructure (such as Pareto efficiently located dams, World Bank, 2017).

(vi) The relationship between hydropower and irrigation in multipurpose reservoirs is pivotal: it has been evaluated that while today roughly 54% of global installed hydropower capacity competes with irrigation and 8% complements it, competition is expected to intensify under a warmer climate (Zeng et al., 2017).

(vii) Besides long-term alterations in the climate system, droughts and floods pose short-term disruption risks to the power sector, with statistically significant reductions in average hydropower utilization rates (-5.2%) and thermoelectric power generation (-3.8%) during drought years compared to the long-term average having been observed (M. T. van Vliet et al., 2016). Overall, water shortages from both long-lived changes in precipitation, evapotranspiration, and extreme events pose the risk of reducing electricity production in hydropower plants, while energy outages can themselves disrupt water distribution facilities.

Co-integration of multiple RE (Figure 6.3c), - e.g. of variable sources like solar PV and wind and hydro used as a solution to increase flexibility and provide power storage (in particular to satisfy peak demand) has multiple benefits. It can trigger win-win solutions for emissions mitigation, renewables share increase in the generation mix, climate resilience of the power sector, and sustainability in the use of water resources.

6.3. Literature review results

The screened literature has been classified into three main categories: (i) studies assessing the potential impacts of climate change on hydropower supply and reliability, both at the global and at the river basin level; (ii) research contributions focusing on the impact of power generation on water availability as a result of withdrawals or consumptive uses e.g. for thermal plants cooling; (iii) the literature on the broad array of additional stressors for water availability, e.g. as a result of economic growth. Before introducing the results of the literature screening, I also report recent studies offering techno-economic analysis of hydropower and power mix expansion pathways for SSA carried out at different scales.

6.3.1. Techno-economic analysis of hydropower in SSA

A gross technical untapped potential of 7.7 PWh/year (Hoes et al., 2017) has been estimated for SSA, of which there remain between 1.4 PWh/year below a cost of $0.10/kWh (Gernaat et al., 2017) and 2.9 PWh/year below a cost of $0.09/kWh (Zhou et al., 2015), i.e. techno-economically feasible compared to other local generation options. These assessments mostly rely on spatially-explicit digital elevation and river discharge information within a cost optimisation modelling framework. Discharge is based on historical long-run averages, although (Gernaat et al., 2017) also test the effect of climate change (under scenario RCP 8.5) on runoff and thus on the remaining technical potential. They observe a moderate increase (4 to 18%) consistently occurring in Africa.

A significant share of the potential is concentrated in sites with very large potential capacity, such as the Grand Inga, in the Congo River (up to 42 GW). (Taliotis et al., 2014) analyse the impact of the project of the continental energy system in a modelling framework, and found that - provided sufficient high-voltage transmission interconnection infrastructure is put into place - the dam could satisfy a substantial part of the power demand in all power pools of SSA. However, the authors do not account for any externality of the project. Also, open questions remain on the continental impact of potential (including climate-induced) generation disruptions at such large-scale projects. With regards to the issue, Deshmukh et al. (2018) assess the feasibility and cost-effectiveness of RE alternatives to the Inga 3 scheme. They find that under most scenarios, the hydropower project would be comparatively more costly than a mix of wind, solar PV, and some natural gas to meet future demand. Similar results are highlighted by (Oyewo et al., 2018).

Irrespective of the large and cheap untapped hydropower potential, a number of studies show that cost-effective pathways that are alternative to heavily relying on new dams exist for SSA. For instance, Wu et al., (2017) claim that the current generation capacity expansion paradigm in SSA, which largely relies on domestic large-scale hydropower schemes, is dominating because of the insecurity and high costs of fossil fuels. The authors however highlight a large number of concerns related to this paradigm, including many aspects discussed in this paper. To provide an alternative, they create a framework for multicriteria analysis for planning RE and map and characterize solar and wind energy zones in the Southern African Power Pool (SAPP) and the Eastern Africa Power Pool (EAPP). They find that RE potential is several times greater than demand in many countries and mostly economically competitive, and thus it significantly contributes to meeting this demand. International interconnections are however necessary to render this potential economically feasible for the region as a whole. Also, interconnections that support the best RE options are different from those planned for a counterfactual scenario of domestic large-scale hydropower expansion. The same direction is pointed by (Barasa et al., 2018), who estimate electricity generation potential throughout SSA (divided into 16 sub-regions) at a hourly resolution according to four scenarios over the transmission grid development. They show that RE is alone sufficient to cover 866 TWh electricity demand for 2030, and that existing hydro dams can be used to balance large-scale solar PV and wind integration. All scenarios represent pathways of substantial diversification away from hydropower, which compared to other RE would have a significant smaller share. The authors highlight that this finding is at odds with the *New Policies Scenario* of the IEA, which projects that by 2040 hydropower may account for 26% of electricity generation in SSA. Similar results are highlighted in Schwerhoff and Sy (2019), who compare results from

Integrated Assessment Models (IAMs), finding that different sustainable energy supply pathways for Africa which are also compatible with the 2C climate target. Some scenarios determine a 100% switch to RE over the medium-run, provided sufficient transboundary transmission infrastructure is put into place.

Another significant aspect concerns the small-scale hydropower potential and its role for delivering electricity access to remote communities. Several technical assessments have been carried out for SSA (Ebhota and Inambao, 2017; Kaunda et al., 2012; Korkovelos et al., 2018), highlighting the significant potential (e.g., 9.9 GW in the Southern African Power Pool, and 5.7, 5.6, and 3.9 GW in the Central, Eastern, and Western African Power Pools, respectively). Least-cost techno-economic electrification models then show (Korkovelos et al., 2019; Mentis et al., 2017) that these technologies can be the cheapest option to provide power to mini-grids in a number of settlements throughout SSA. Yet, little research has hitherto been performed to assess the reliability and vulnerability of such small-scale technologies to long-lived changes in the discharge or short-lived disruptions.

Finally, Szabó et al. (2016) show that in an array of settings the least-cost option for achieving electrification of local communities in SSA consists in transforming currently existing but non-powered dams into electricity-generating schemes. Overall, the authors calculate a potential of 243 MW at a moderate cost of $365.7 million, which could supply nearly 4 million people with electricity.

6.3.2. Climate change impacts on hydropower

Table S2 (in the Appendix) reports and briefly summarises the main reviewed studies covering the projected impacts of climate change on hydropower in SSA. The literature can be classified among three key dimensions: (a) the geographical scope, with 6 reviewed studies assessing the global scale, 5 papers examining broad African regions, and 14 contributions analysing specific river basins or countries; (b) the methodology, mostly including integrated electricity-hydrology model-based studies, and (c) the climate scenarios considered, with most studies assessing the RCP (Representative Concentration Pathways) and SRES (Special Report on Emissions Scenarios) scenarios.

Global or regional scale studies evaluating changes in global hydropower potential caused by potential changes in climate conditions include the following:

Hamududu and Killingtveit (2012) use an ensemble of simulations of regional patterns of runoff changes and found that on a global scale the absolute magnitude of change is projected to be small and positive (>+1%) for the hydropower system in operation today, but substantial heterogeneity exists.

Most negatively affected SSA countries (in terms of percentage change of total currently operating hydropower output by 2050) include Mozambique (-9.5%), Namibia (-21.2%), South Africa (-11.6%), and Zimbabwe (-10.4%). Among countries potentially benefiting from climate change for hydropower generation, there figure Burundi (+13.1%), Rwanda (+15.1%), Uganda (+14.9%), and Tanzania (+12.9%).

(Turner et al. (2017c) employ a coupled global hydrological and HPP (hydropower plant) model with downscaled, bias-corrected climate simulations (under RCPs 4.5 and 8.5), to explore consequent impacts on the power mix and associated emissions and investment costs using an integrated assessment model. They find significantly altered power sector CO2 emissions in several hydropower-dependent regions and estimate the global 21st century investment necessary to compensate for deteriorated hydropower generation caused by climate change at $1 trillion. For SSA, under the two RCP scenarios, they estimate an increase in the 0.07-0.13 EJ (exajoule) range in hydropower output in East Africa by 2100 with respect to today’s level, coupled with a decrease in carbon dioxide emissions (up to 2.79 MtC/year) and in required energy investments (up to -$72.6 billion), while for Southern and West Africa they find decreases in the hydro output of 0.01 and 0.03 EJ, respectively. These are associated with increase of 0.02-0.54 MtC/year on power sector emissions across the two regions, and a $4.4-13.4 billion impact on cumulative power sector investments.

Turner et al. (2017b) further improve the model simulating HPP with a detailed dam model that accounts for plant specifications, storage dynamics, reservoir bathymetry and operations. They show that the inclusion of these features can have a non-trivial effect on the simulated response of the hydropower production to changes in climate factors. Here, results are expressed as the average country-level hydropower output change, considering A2 and B1 SRES scenarios and different models. The strongest negative change in hydropower output is found in West Africa: Togo (-14.4%), Ghana (-14.5%), Mali (-13.7%), Guinea (-12.9%), Cˆote d’Ivoire (-15.7%), Nigeria (-15.8%).

Van Vliet et al. (2016) predict reductions in usable capacity for 61-74% of the hydropower plants and 81-86% of the thermoelectric power plants worldwide for 2040-2069. For the African continent, they highlight moderate declines (around -0.9%) in hydropower output by 2050 for both RCP 2.6 and 8.5, and more substantial declines (around -5.2-17.8%) in thermoelectric power if no adaptation measures are implemented.

M. T. H. van Vliet et al. (2016) carry out a multi-model assessment of global hydropower and cooling water discharge potential under RCP2.6 and RCP8.5

climate change scenario over five GCMs (general circulation models). For SSA they predict large increases of hydropower output (>20%) in Central Africa and considerable declines (<-20%) in North Africa and parts of Southern Africa.

Cervigni et al. (2015) present a comprehensive analysis of the future of water-related infrastructure (including both hydropower and irrigation in agriculture) under IPCC (Intergovernmental Panel on Climate Change)'s RCP warming scenarios. The authors focus on the question of how to design and build the essential infrastructure needed for Africa's development, while factoring in and addressing the challenge of climate resilience. The study covers seven major river basins (Congo, Niger, Nile, Orange, Senegal, Volta, and Zambezi) and all four of SSA's electric power pools (Central, Eastern, Southern, and Western). It is argued that failure to integrate climate change in power and water infrastructure could entail, in dry scenarios, losses of hydropower revenues in the 10-60% range with respect to a no-climate-change scenario (in part because the transmission lines and power trading agreements needed to bring the extra hydropower to the market could not be available). Threefold increases in consumer expenditure for backstop energy (e.g. diesel generation) are projected under the driest scenarios, with significant impact on infrastructure investment and future power mix configurations. Climate change is projected to have the largest impact on electricity consumer prices in the Southern African Power Pool, where transmission lines are limited and the percentage of hydropower in the total installed capacity is high. For instance, hydropower generation could decline by more than 60% in the Zambezi basin. On the other hand, an unexploited wetter climate (in terms of underdeveloped capacity) could imply forgone revenues of 20-140% vis-`a-vis the baseline.

Cole et al. (2014) assemble an extensive spatial dataset for Africa from geographically based information on daily precipitation, soil conditions, power plants, and energy network grids. They find that while on average current plans for African dam building are well matched with river-flow predictions, in most countries a higher output variability would be witnessed, and a reduced hydropower production would still occur in some others, including Guinea, Mozambique, Sierra Leone and Niger.

M. T. van Vliet et al. (2016) quantify the impacts of drought episodes and warm years on hydroelectric and thermoelectric available capacity. They show that hydropower utilisation rates were on average reduced by 5.2% and thermoelectric power by 3.8% during drought years compared to the long-term average for 1981-2010, while during major drought years, hydropower showed declines in the 6.1-6.6% range and thermoelectric power in the 4.7-9% range. Among the global regions considered, they observe the highest interannual variability in utilisation rates of hydropower in Southern Africa (the only region of SSA considered in the study).

Besides global and continental-scale studies, many regional analyses have also been carried out. (Sridharan et al., 2019) assess climate vulnerability of hydropower infrastructure in the Eastern African Power Pool. They find that failing to perform climate-resilient infrastructure investment (found to be a plan optimised for a slightly wetter climate compared to historical trends) can result in significant electricity price fluctuations, in particular in Uganda and Tanzania.

Stanzel et al. (2018) apply climate data of an array of Regional Climate Model simulations in a water balance model for the case of West Africa, based on RCP4.5 and RCP8.5 until 2065. The results show mixed trends, with median results of the model ensemble for the relative change in rivers' discharge in the range of ±5%. The ensemble agrees upon the significance of the results in a number of sub-regions, including stronger decreases in the north and east of West Africa and pronounced increases mainly in the southwest.

Kling et al. (2015) and Kling et al. (2014) assess future climate change impacts in the Zambezi basin - hosting three of the largest hydropower schemes in SSA, the Kariba (1470 MW), Cahora Bassa (2075 MW) and Kafue Gorge (990 MW) - for existing and planned major hydro plants, based on global climate model projections from the CMIP5. The authors refer to RCP4.5 and account for moderate economic growth to factor in changes in withdrawals for agricultural irrigation. They downscaled climate change signals at the stations to construct future time-series of precipitation and temperature at a number of sub-basins. Their results - characterised by significant uncertainty in future precipitation levels - show that by 2050 annual discharge could decrease by 20%, with sub-basin heterogeneity but diffuse negative changes. Such declining trends in discharge are predicted to worsen, with declines in the 40-55% range by the end of the century, posing a great risk for water resources management in the Zambezi basin. Runoff is found to be mostly sensible to changes in precipitation rather than in temperature, the former being however also the most uncertain variable.

Spalding-Fecher et al. (2016) also assess the vulnerability of hydropower production in the Zambezi River Basin to the impacts of climate change, but they include in the analysis more specific focus on irrigation development. Using the Water Evaluation and Planning (WEAP) tool, they find that for both existing (Cahora Bassa) and planned downstream schemes (Mphanda Nkuwa) prioritising irrigation demand over hydropower could severely compromise the plant's output and impair the feasibility or limit the cost-effectiveness of expansion plans. At the same time, the generation at upstream HPP (Karibe) is highly vulnerable to a drying climate, while new projects (Batoka Gorge) and expansions may not reach the production levels forecasted in feasibility studies.

Harrison and Whittington (2002) evaluate the relationship between climate change scenarios and the future technical and financial viability of hydro development. They elaborate on the case study of the not yet built 1,600 MW Batoka Gorge project on the Zambezi river, upstream of Lake Kariba. Their findings suggest that - under the examined climate change scenarios - significantly altered river flows and adverse power production and financial performance would occur (up to 19% of target production unmet, up to $3.8 million per month of forgone revenues and up to +$0.40 in unit cost of electricity) vis-`a-vis a no climate change scenario.

Conway et al. (2017) rely on cluster analysis to define regions of coherent rainfall variability in East and Southern Africa to illustrate exposure to the risk of hydropower supply disruption of current and planned hydropower sites. The authors forecast substantial increases in the exploited capacity in the Nile and Zambezi river basins, and find that by 2030, 70% and 59% of the total hydropower installed capacity (including HPP currently planned or under constructions) would be located in a single cluster of rainfall variability (i.e., areas experiencing similar rainfall patterns) in EA and SA, respectively. According to the authors, unless robust power interconnection infrastructure is put into place, this would increase the risk of concurrent climate-related electricity supply disruption and power rationing in the two regions because dry years will negatively affect water storage at all reservoirs and their ability to subsequently refill.

Further regional or basin-level studies, heterogeneous in the methodology adopted, include the following: (Beilfuss, 2012) on the hydrological risks and consequences of climate change for Zambezi River Basin dams and (Spalding-Fecher et al., 2016) on the vulnerability of hydropower production to the impacts of climate change and irrigation development in the same area; (Boadi and Owusu, 2017) on climate-induced hydro variability and disruptions in Ghana, and (Kabo-Bah et al., 2016) on climate trends in the Volta River Basin and their potential impact on hydropower generation; (Kizza et al., 2010) providing future hydropower scenarios under the influence of climate change for the riparian countries of the Lake Victoria Basin; (Loisulie, 2010) assessing the vulnerability of the Tanzanian hydropower production to extreme weather events; (Oyerinde et al., 2016) estimating the projected impacts of increased GHG emissions on the Niger basin at the Kainji hydroelectric plant and implications for local power production; (Bunyasi, 2012) studying the case of the Seven Forks Project to assess the climate vulnerability of hydroelectric resources in Kenya; (Mukheibir, 2017, p. 201) adopting a similar approach for large hydroelectricity schemes in

Southern Africa. (Uamusse et al., 2017) focusing on the case of Mozambique, where the Cahora Bassa dam provides an important share of the domestic power supply - in particular in the northern provinces - despite 65% of the total power generated at the dam being exported to South Africa, projecting a capacity reduction in all hydro plants in the country, with Cahora Bassa falling from the current 2,075 MW to 1,822 MW; and (Karekezi et al., 2012) providing an assessment of the economic impact of recent droughts-induced hydropower capacity reduction and disruptions in the East and Horn of Africa region.

A comprehensive assessment shows that irrespective of large uncertainty in the projected change in precipitation levels and patterns, agreement is found over projections that East Africa could positively benefit from a warmer climate in terms of hydropower output, West and Southern Africa would be subject to negative impacts, while Central Africa is prone to be less affected. For all the predictive studies under examination it must be remarked that substantial uncertainties emerge when modelling the impacts of climate change on hydrological variables and hydropower output. These uncertainties regard both the magnitude of projected climate alterations (in particular for precipitations), and the degree of potential water abstraction from planned future upstream dams.

6.3.3. The impact of power generation on water availability

Power generation is itself a water-intensive activity in terms of both withdrawals (water removed from a source) and consumption (the volume withdrawn and not returned to the source due to evaporation or transport). The (IEA, 2016) estimates that, on a global scale, the power sector accounts for 10% of total water withdrawals and 3% of consumption, i.e., 88% of total water withdrawals and 36% of water consumption volumes of the energy sector. Fossil fuels are by far the thirstiest power generation sources, with 230 bcm (billion cubic meters) of water withdrawn worldwide for cooling purposes in 2014. However, withdrawals and actual consumption are largely variable across technologies and depend primarily on the cooling technology in question.

The effective water consumption of hydropower varies depending on technology type (e.g. reservoir vs. RoR plants), reservoir size, local climate, and total demand from all water users (IEA, 2016). Reservoirs serve as a major source of global energy storage, and a majority of the water withdrawn is returned to the river after passing through turbines. As a result, the amount consumed is highly site-specific. Nonetheless, this does not imply that water availability is neutral to hydropower, and vice versa. 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.

Table S3 (in the Appendix) reports the reviewed studies (Bakken et al., 2017; Davies et al., 2013; Fricko et al., 2016; Mekonnen et al., 2015; Mekonnen and Hoekstra, 2012; Meldrum et al., 2013; Mouratiadou et al., 2016) on the impact of power generation - both from fossil fuels and hydropower - on water resources. The focus is on studies at the global or SSA scale, while I acknowledge but do not include similar studies on the UK (Byers et al., 2014), the US (DeNooyer et al., 2016) and China (Zhang and Anadon, 2013).

The literature suggests that 96.4% of the consumptive water footprint of electricity and heat production in Africa stems from hydropower, with peaks of average 450,000 - 496,800 $l \cdot MWh^{-1}$ in hydropower-dependent countries (Mekonnen et al., 2015). To put the figures in perspective, the median water withdrawals from combined cycle once-through-cooled gas-fired plants stands at 43,100 $l \cdot MWh^{-1}$, and that of general once-through-cooled coal-fired plants is at 137,600 $l \cdot MWh^{-1}$, with a very similar value for steam gas-fired plants (Macknick et al., 2012). Concerning withdrawals (which include all water diverted) from its source, the figures stand at 669,600 l·MWh−1 at Cahora Bassa and at 2,239,000 $l \cdot MWh^{-1}$ at Lake Kariba (Mekonnen and Hoekstra, 2012).

6.3.4. Additional stressors for water availability

According to the UN (United Nations Population Division, 2017), the population of SSA is expected to reach the 2.75-5.5 billion range by 2100 from the current 1 billion, and hence to undergo a quasi-threefold growth in the most conservative scenario. This means that - assuming constant per-capital withdrawals and efficiency in water use - consumption, industrial use and other withdrawals would increase. However, if this assumption is released, two effects will work in opposite directions: on the one hand the potential (by know-how, technology and infrastructure) to increase water use efficiency, which as of today is relatively low; on the other, the concrete chance that increasing development and well-being result in rising per-capita water demand, through both higher water use and increased consumption of products with large water footprints (such as meat). The link has been previously investigated by several studies, among which (Buitenzorgy and Ancev, 2013; Cole, 2004; Duarte et al., 2014; Flörke et al., 2013; Katz, 2015). Most assessments agree on an inverted-U shape statistical relationship between per-capita income and water use, with the estimated turning points found at income levels that have only been reached in the developed regions. (Cole, 2004) projects developing regions' (including SSA) per capita and total water use to increase in the coming decades, while they argue that the current extreme inefficiencies in use might be mitigated with sound policy and technological advances.

6.4. Data evidence results

Here, I investigate the historical evolution of hydropower capacity, generation, and capacity factors in hydropower-dependent countries, to understand the heterogeneity in the diversification trends observed. I also collect extensive information on capacity currently under construction or having secured finance, to understand how regional power mixes may evolve in the near future. Then, drawing from a long-run drought database, I evaluate if and to what extent the frequency and intensity of extreme events has evolved throughout the twentieth century. Lastly, I illustrate the potential evolution of hydropower under the downscaled CMIP5 climate projections under different warming scenarios to provide evidence of future potential stress on hydropower.

6.4.1. Diversification: trends and pathways

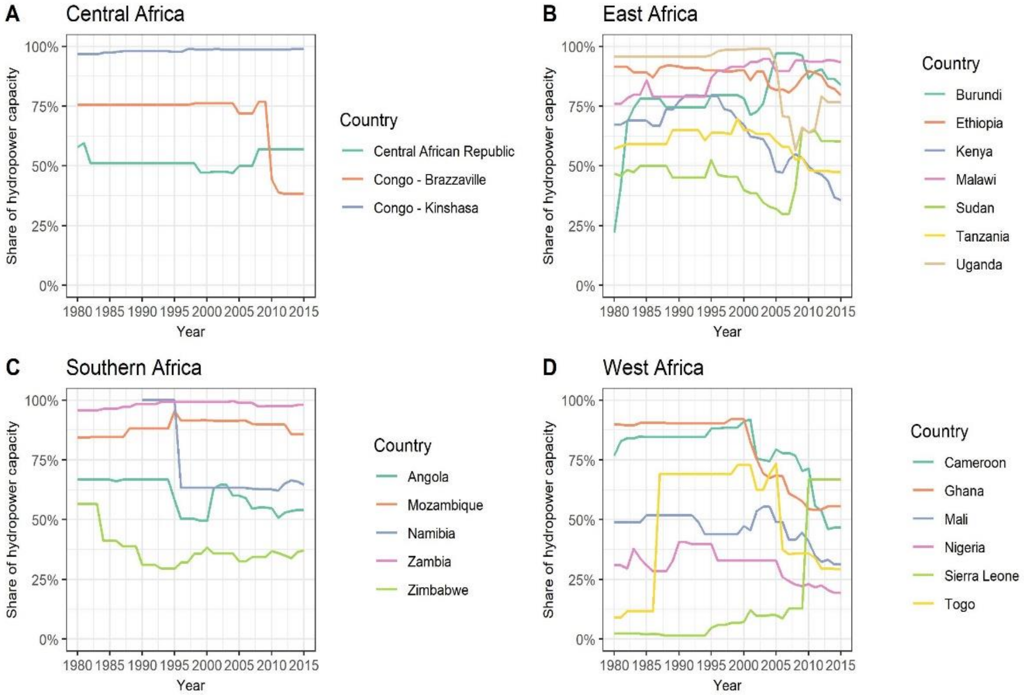

Figure 6.4: *Evolution of share of hydropower over total capacity. Elaboration on data from (US EIA, 2017).*

Figure 6.4 and Figure 6.5 plot the evolution of the share of hydropower over total capacity and generation, respectively, for the period between 1980 and 2015. The figures are reported for hydropower-dependent countries of SSA under examination. Here, both countries with a hydropower share > 50% of total generation, and further countries deemed potentially affected by the issues discussed in the paper are included. Countries are grouped by region (Central, East, West, Southern), so as to highlight the different trends of diversification that have been followed across neighbouring countries. Refer to the Appendix to Essay 6 for a map showing the regional classification adopted in this paper.

The numbers on the share of hydropower generation show that only some countries have successfully pursued a diversification strategy over the last three decades. These include Tanzania (panel B), where hydropower fell from 95% in year 2000 to a low of 37% in 2015 thanks to the installation of 700 MW of gas-fired plants over the last decade; the Republic of Congo (panel A), where the delivery of a 300 MW gas-fired power plant in 2011 led to a temporary diversification (but further 1,600 MW of new hydropower capacity are planned); Ghana (panel D), where hydropower fell from a share of 80% in 2000 to around 50% in 2015. However, in the case of Ghana diversification via gas-fired capacity addition tells only part of the story for the reduction of the share of hydropower over total generation. Droughts and consequent water level reductions of Lake Volta over the last decade have in fact been significant contributors to the observed drop in hydro generation and consequent power supply issues experienced since (Boadi and Owusu, 2017), leading to deployment of emergency capacity.

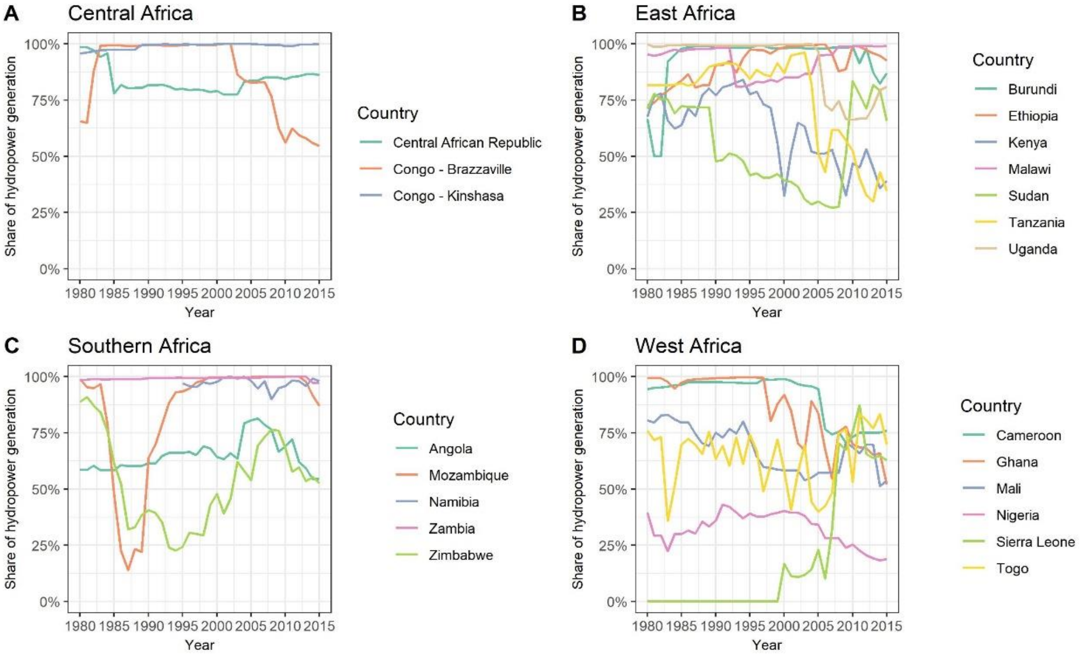

Figure 6.5: Evolution of share of hydropower over total generation. Elaboration on data from (US EIA, 2017). Source: author's calculations.

This and analogous trends are detected when examining the trend in the national hydropower capacity factors reported in Figure 6.6. Capacity factors are defined as the effective hydropower output over the total maximum theoretical output over a certain time period (here: yearly). Note that the dipping to a near-zero level in Mozambique between the early 1980s and the late 1990s is owing to the damaging of the dam during the civil war years.

Figure 6.7a shows the generation capacity currently under construction or for which financing has been already procured. The figures are clustered by region and technology. The figures exclude proposed or planned schemes which are still in the feasibility assessment or for which financing has not yet been secured. Information has been retrieved from (Cross-border Information, 2017), as well as from an extensive screening of recently published African news reports. Figure 6.7b shows the change in hydropower share over the total capacity that would result from the completion of those construction works (as compared to the current situation).

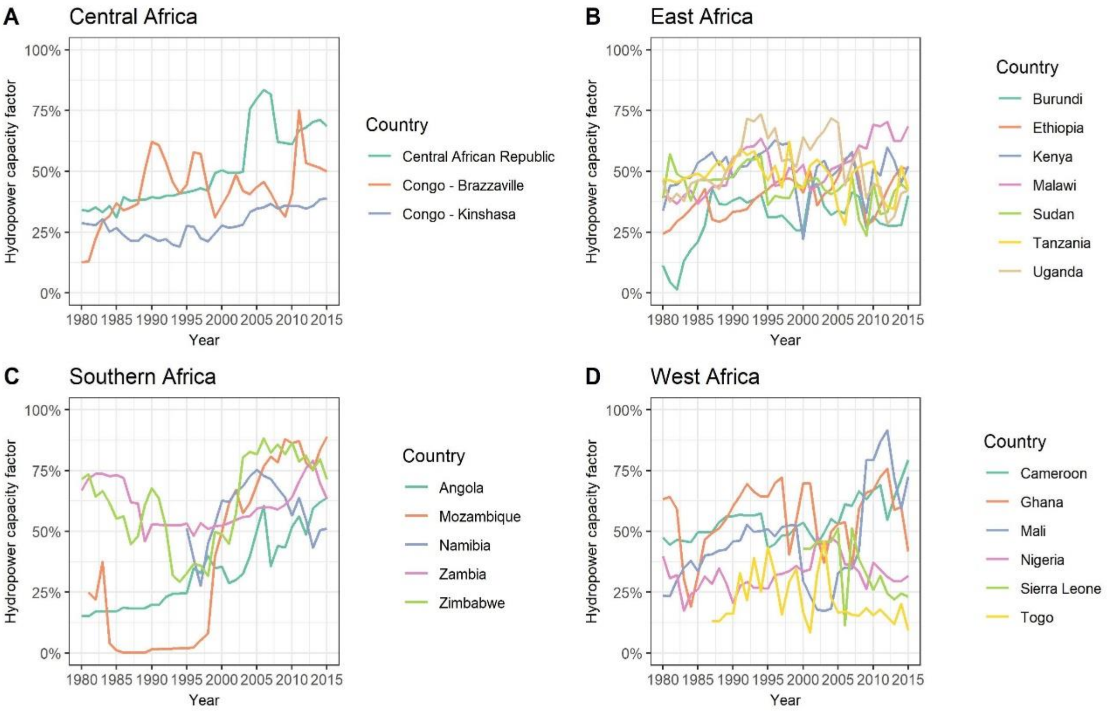

Figure 6.6: Evolution of hydropower capacity factors. Elaboration on data from (US EIA, 2017). Source: author's calculations.

The figures reveal that the largest undergoing capacity additions are concentrated in a limited number of countries, and only in West Africa and partially in East Africa (mostly in Kenya) large-scale non-hydro expansions are undergoing. GW-scale hydropower capacity is being added in the DR Congo, Ethiopia, Tanzania, Angola, and Guinea. Gas-fired generation is the second technology by planned capacity, especially in Ghana, Nigeria, and Angola. However - crucially - a hydro-to-gas transition for baseload capacity would not be compatible with the Paris Agreement's goals over the long run. Countries with strong, RE-based diversification away from hydropower currently include Kenya (with a prominent role of geothermal and wind) and Uganda (with substantial solar PV capacity additions). While Ghana is implementing significant RE projects in solar PV, wind, and tidal power, the bulk of the planned capacity additions are based on gas.

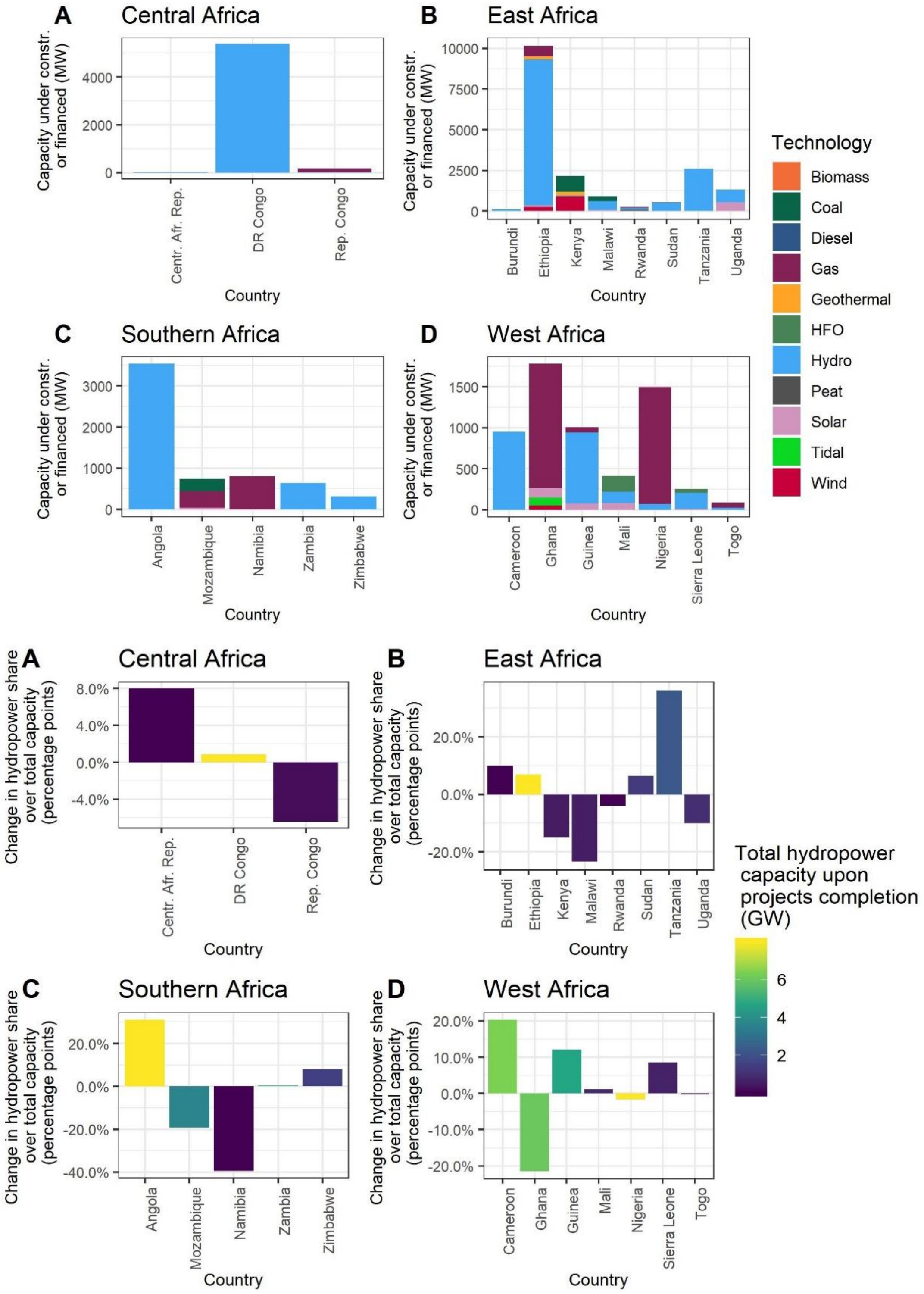

Figure 6.7: (a) Power generation capacity currently under construction or financed, by technology and region. (b) Change in the projected share of hydropower (in percentage points) in total capacity upon completion of the currently under construction/financed

power plants. The colour shading indicates each technology and the total installed hydropower capacity in (a) and (b), respectively. Source: author's calculations.

Overall, in the short-run diversification - at least in terms of domestic installed capacity - will be strongest in Namibia (-39%), Malawi (-23%), Ghana (-21%), Mozambique (-19%), and Kenya (-15%), all countries which over the last years have been affected by drought-related outages. On the other hand, hydropower dependency will become stronger in Tanzania (+36%), Angola (+31%), Cameroon (+20%), Guinea (+12%), Burundi (+10%), Sierra Leone (+9%), the Central African Republic (+8%), and Zimbabwe (+8%).

6.4.2. Drought incidence

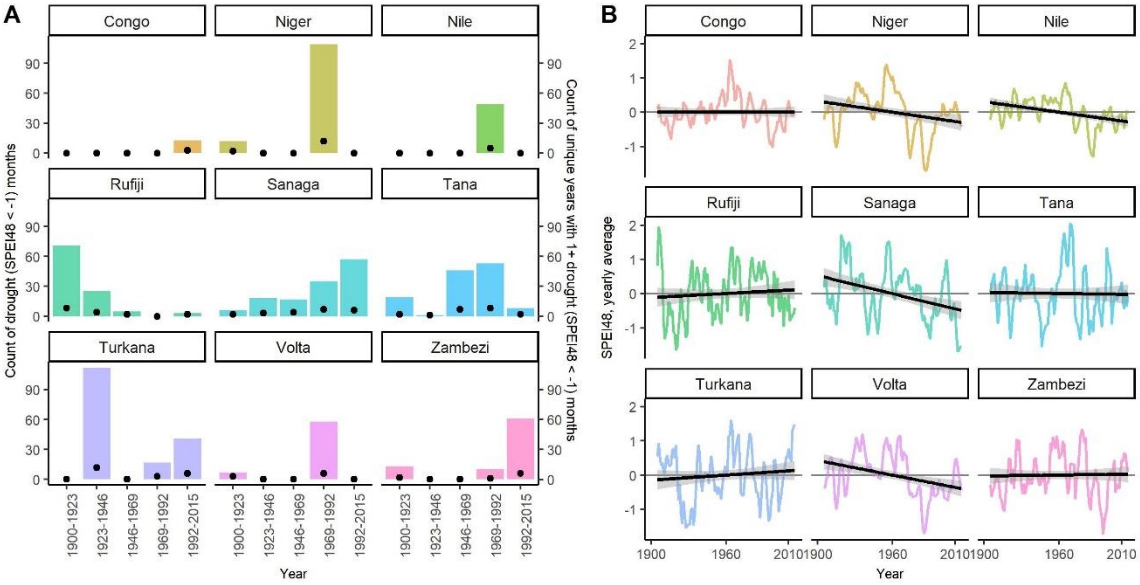

Figure 6.8: Historical representation of droughts in SSA rivers, (a) drought (SPEI48 ≤−1) months per period (bars) and count of unique years with 1+ severe drought months (dots); (b) yearly average SPEI48. Elaboration on data from (Beguería and Vicente-Serrano, 2017), developed using monthly data from (University Of East Anglia Climatic Research Unit (CRU) et al., 2017). Source: author's calculations.

To assess the evolution of the incidence of drought events in the main river basins of SSA, I retrieved the World Resources Institute's major watersheds of the world shapefile (World Resources Institute, 2006) and extracted the monthly time-series of the average SPEI48 (Standardized Precipitation-Evaporation Index) (Beguería and Vicente-Serrano, 2017) over each of the nine major basins in terms of current installed hydropower capacity. Here, 48 denotes the scale of the index, in which dryness and wetness are defined as a function of the time scale over which water deficits accumulate. A long-term scale allows detecting long-lived, prolonged droughts, while short-term scales are better suited for droughts covering a limited period of time, such as the growing season in agricultural studies. The index is calibrated on precipitation and evapotranspiration data between 1950 and 2010. The 60-year calibration time-scale allows accounting for natural variability and seasonality and allows thus detecting anomalies. Refer to the Appendix to Essay 6 for a map showing the location and extent of each basin. The data is then aggregated to produce: (i) counts of the number of drought months over 23-year periods (in order to have a consistent width across periods); (ii) counts of years that witnessed at least a drought month, and (iii) yearly average values for the SPEI48 (the classification of which is reported in the Appendix to Essay 6). The metrics shed light on the frequency of extremes, and on the general trend in the average wetness/dryness level, respectively.

The results (Figure 6.8) show that the frequency of drought months (here defined as months with a SPEI48 < -1) has changed heterogeneously across river basins during the twentieth century. The number of drought months seems to have been gradually growing in the Sanaga, Turkana, Volta, and Zambezi river basins, although many of these trends are not linear. Furthermore, the Congo, Niger, and Nile basins - previously only mildly affected by droughts - have experienced a very significant drought incidence in the last decades of the twentieth century. The only main exception is found for the Rufiji basin, where the incidence of droughts has declined during the past century. At the same time, the dots in Fig. 8a show the number of years in each 25-year period where at least 1 month of drought was experienced, giving a clearer picture on the frequency of droughts, besides their total duration. Again, this reveals non-linear, basin-specific trends. At the same time, the yearly average measured SPEI48 (Figure 6.8b) has witnessed a robust decline, implying a drying of the local climate, in the Niger, Nile, Sanaga and Volta river basins, while statistically insignificant changes characterise all the remaining basins assessed.

6.4.3. Climate change projections

Further evidence to support the discussion of the results of the review is derived from downscaled CMIP5 (Coupled Model Intercomparison Project - phase 5) data for two RCP scenarios (2.6 and 8.5) from the IPCC (corresponding to 1.5 degree warming by 2100 and a business-as-usual trajectory, respectively). Data is averaged across the output of the 19 models in the CMIP5 consortium on country-level. Figure 6.9 and Figure 6.10 show the seasonal charts (i.e., the monthly profile) of the projected change in the mean precipitation and temperature across East, West, Central, and Southern Africa with respect to the historical mean of each specific month.

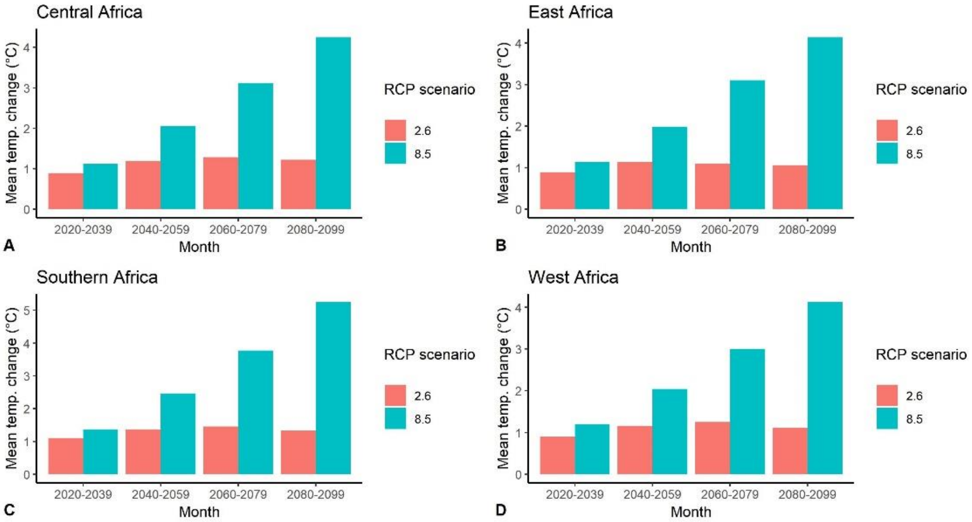

Figure 6.9: Seasonal plot of projected temperature change (compared to long-term historical averages) under two RCPs (CMIP-5 models median) over the 21st century for (A) Central Africa, (B) East Africa, (C) Southern Africa, and (D) West Africa. Elaboration on data from (Taylor et al., 2012).

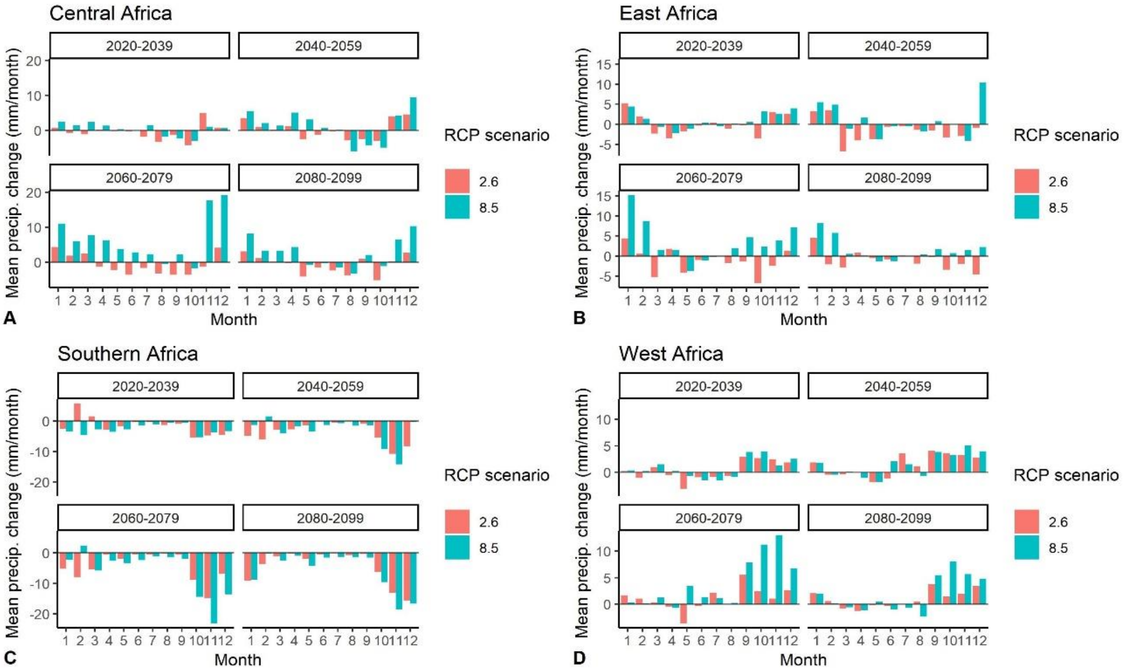

Figure 6.10: Seasonal plot of projected precipitations change under two RCPs (CMIP-5 models median) over the 21st century for (A) Central Africa, (B) East Africa, (C) Southern Africa, and (D) West Africa. A solid line is drawn at 0, to separate positive from negative change. Elaboration on data from (Taylor et al., 2012).

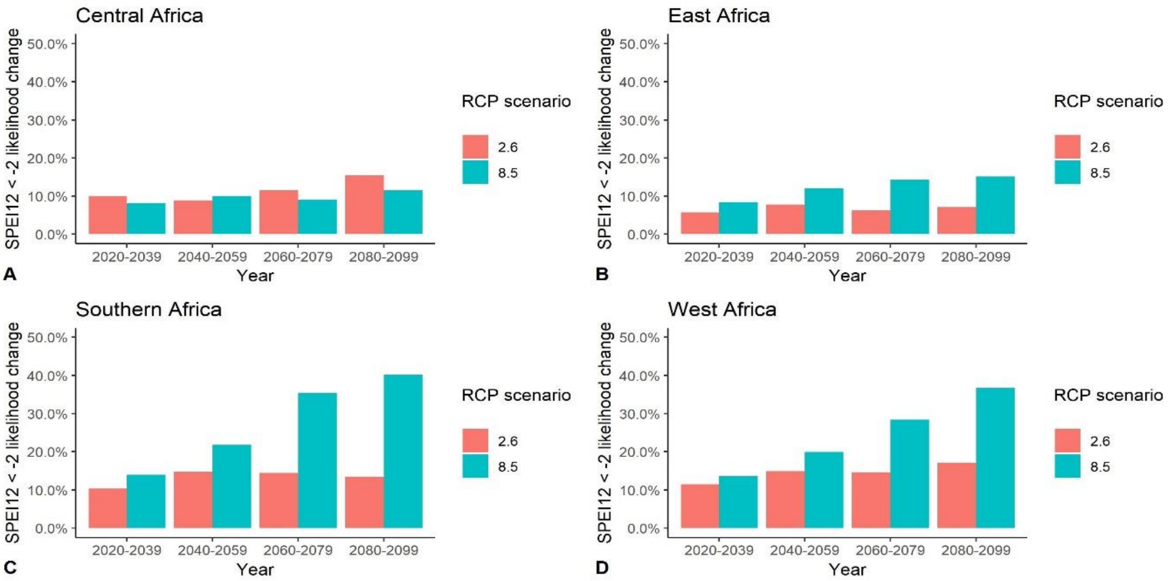

Figure 6.11: plot of projected severe drought (SPEI12 < -2) likelihood change change under two RCPs (CMIP-5 median) for (A) Central Africa, (B) East Africa, (C) Southern Africa, and (D) West Africa. Elaboration on data from (Taylor et al., 2012).

Concerning the projected shifts in the monthly profile of mean temperature (in ◦C) vis-`a-vis a RCP 2.6 of mitigated climate change, an average increase of 3.5◦C and up to 5◦C by 2090 would occur across the different regions in a rather similar fashion (Figure 6.9). The largest temperature increase would emerge after 2040 under an RCP 8.5 scenario. However, in countries that already have higher-than-average temperatures at the continent level, such as Congo, Sudan, Ghana, Togo and Mali, those changes might exert an ever stronger effect on evapotranspiration.

Predicted changes in the monthly profile of mean precipitations under the two RCPs (Figure 6.10) provide instead a general picture of countries that could be more or less resilient to different degrees of warming in terms of water availability via direct rainfall. Trends are more heterogeneous than for temperature, and yet they show that in some regions (in particular in East and Central Africa) a larger change in radiative forcing could also have a wetting effect on the local climate with respect to a heavy abatement scenario. The most consistent declines in rainfall under unmitigated climate change are forecasted in Southern Africa, where rainfall could drop of up to 20mm/month in the wet season months (October to March) compared to the historical average in those months.

Finally, the annual severe drought likelihood change with respect to the average recorded between 1986-2005 describes the projected change in the likelihood of an extreme drought (defined as a SPEI < -2) to take place under the RCP scenarios 2.6 and 8.5 with respect to the historical incidence (Figure 6.11).

Irrespective of the predicted direction and magnitude of change in monthly precipitation patterns, in West, East, and Southern Africa RCP 8.5 is projected to lead to a consistently higher likelihood of extreme drought events to occur. While in East Africa the relative discrepancy between the predictions for two RCPs by 2100 is more limited (around +7.5%), in others the spread is substantial, and chiefly in Southern (+25%) and in West (+20%) Africa. Central Africa shows instead very little discrepancy in the probability of SPEI12 < -2 periods to occur, and for the region the RCP2.6 results in an even slightly higher likelihood for severe drought incidence than RCP8.5.

6.5. Discussion

A large number of scenarios project hydropower as the main technology for procuring the on-grid capacity expansions helping to satisfy the growing demand for power in SSA, and achieving the SDG 7 of universal access to modern energy. HPP are deemed key assets thanks to the large untapped potential throughout SSA and the low running costs. Furthermore, international development institutions and national governments have been supporting hydropower thanks to its low carbon intensity. For instance, hydropower is considered eligible for the credits of the Clean Development Mechanism (CDM), an emissions reduction program launched under the Kyoto Protocol (although life-cycle assessment studies have found instances where biogenic methane and carbon dioxide emissions stemming from artificial reservoir systems are significant, Hertwich, 2013; Kumar and Sharma, 2012; Zhang and Xu, 2015).

Recently completed large schemes include the 250 MW Bujagali dam in Uganda, a 300 MW plant in Tekeze canyon in Ethiopia, and the 120 MW Djibloho dam in Equatorial Guinea. Significant expansion plans exist with different HPP under construction and massive projects proposed, such as the 39 GW Grand Inga Dam in DR Congo, expected to cost at least $50 billion and which has recently regained momentum (Financial Times, 2018). Other large ongoing or planned projects include the 6 GW Grand Renaissance dam on the Blue Nile river and the 1.8 GW Gibe III dam on the Omo river, both in Ethiopia, a 1.6 GW scheme on the Zambezi river basin between the Zambia-Zimbabwe border on the Batoka Gorge, and the 1.5 GW Mphanda Nkuwa project downstream of the Cahora Bassa reservoir in Mozambique.

As a result of those potential large-scale expansions, the climate-water-energy nexus is prone to become increasingly important in SSA. Water is a key node in development and economic growth dynamics of the continent owing to its strong interconnections it presents with a number of economic sectors, in particular where adaptive capacity is constrained. Climate change is expected to affect water availability for several end-uses, including hydropower and cooling in thermal power plants. Projected impacts (in particular those on precipitations and drought events occurrence) are, however, spatially and temporally heterogeneous and multiple sources of uncertainty exist at different scales as a consequence of modelling and parametric uncertainty (Arnell and Gosling, 2013; Schewe et al., 2014).

The results of our review show that the problem is highly basin-specific: some countries could face harsher issues due to structural long-run declines in generation potential (mostly in West and Southern Africa, although even within regions there can be large discrepancies between different river basins, see (Stanzel et al., 2018), while others (chiefly in East Africa) would benefit from increased yearly aggregate potential but also be more affected by extreme events, and some may not be substantially impacted. Changing seasonality patterns can also play an important role in the energy-water nexus, both in terms of streamflow and of electricity prices, and thus of revenue fluctuations (Gaudard et al., 2018). Therefore, dam planning must be careful and take into account the potential changes in river discharge and the increasing evapotranspiration trends among reservoirs as a result of a warmer climate (also depending on the global emission pathway followed in the coming decades).

Given the already high reliance on hydropower of a number of countries, risks of severe power disruptions (or of inter-sectoral competition for water resources) are likely to intensify if sound energy policy aimed at diversification, co-integration of different sources, and resilient and adaptive dam management (Kim et al., 2017) over multiple future scenarios is not implemented. In particular, hydropower generation is associated with the highest risks in countries where little alternative generation capacity is available and transboundary high-voltage transmission infrastructure for exchanging power is weakly developed. Combined, these could result in declining long-run hydro generation as well as in occasional outages in periods when multiple stressors overlap. This is particularly challenging in countries where the bulk of new base-load power additions will also be hydropower, which, if failing, may lead to substantial under-provision issues.

It is therefore crucial to design long-run strategies including power mix diversification for many SSA countries. Care must be taken in designing diversification pathways in the coming years: heavily expanding gas, coal, and diesel-fired plants - which could be considered less insecure than hydropower irrespective of resources price fluctuations - may set countries on a higher carbon-intensive pathway than those agreed in their Nationally Determined Contributions (NDCs). Different options exist, such as the possibility that part of the back-up stems from decentralised generation solutions (e.g. off-grid PV installed by grid-connected consumers), and planning power systems to integrate diverse zero-carbon sources (solar, wind, water, etc.) and technological advancements for balancing and storage. The success of these options depends on their strategic integration in the governmental energy planning. Energy security objectives and policy must be developed hand in hand with potential emissions mitigation and through the adoption of climate-resilient infrastructure and projects. Renewables can contribute to breaking the feedback loop between fossil fuels combustion, water withdrawal and consumption, and climate change, and in turn positively impact on water, food and energy supply, as well as boost economic growth prospects (refer to the framework presented in Fig. 6.3a). At the core of these linkages lie an integrated and effective energy and climate policy capable of recognising interdependencies, including those that will become stronger in the coming years

Multidisciplinary research plays an important role in quantifying potential climate change impacts on power generation security so as to provide policy makers with figures to inform their cost-benefit-analysis and infrastructure investment decisions (Frumhoff et al., 2015). Concerning the specific case of the impact of climate change and extremes on hydropower generation in SSA, both an analysis of energy, economic, and social impacts of short-lived extremes jeopardising generation in hydropower-dependent countries (e.g. (Falchetta et al., 2020)), and model-based research on long-term water supply under different energy, economic, climate, and demographic scenarios (e.g. (Sridharan et al., 2019; Vinca et al., 2019)) are deemed of great significance. Ever more openly available, accurate, and standard-quality remotely-sensed and modelled river discharge data are likely to allow a new level of insight in this sense. Energy-climate-economy IAMs, and in particular regional-scale nexus-oriented ones, can provide additional insights. Their coupling with basin-level hydrological models under different potential futures could yield greater and more detailed information on water stress risks in different regions, and thus inform policy makers on the consideration of hydropower capacity expansion as well as on the climate-induced supply disruption risks.

6.5.1. Implementing hydropower in sub-Saharan Africa: the way forward

Recent years have witnessed a steep increase in the construction of hydropower dams, including in SSA (Zarfl et al., 2015). At the same time, the remaining techno-economical potential in the continent is large. An effective implementation of new schemes requires the adoption of a nexus approach (de

Strasser, 2017), including within the modelling tools adopted by energy planners. These should be able to co-optimise energy-water-food systems at a transboundary scale in order to assess complementarities beyond the surroundings of the scheme being planned. This is crucial to avoid dam planning based only on energy-system optimisation, which can easily lead to strong impacts on livelihoods, the agriculture sector, and local livelihoods, which might render the overall project's cost-benefit-analysis negative. Transboundary planning thus requires bringing the energy planning dialogue at a regional scale, also because the technical hydropower potential is defined at the watershed, and not at the country level (de Souza et al., 2017).

Furthermore, moving to more flexible dam management strategies, where hydropower is not only a baseload technology but also a balancing solution for VRE integration, may be a very meaningful prospect for promoting a low-carbon energy development in parts of SSA (Sterl et al., 2019, 2018). This could prevent a significant share of the uptake of gas and coal-fired thermal plants. The approach could also reduce the need for very large-scale hydropower schemes (Deshmukh et al., 2018), which often are associated with substantial environmental and social impact.

Finally, as this review has highlighted, hydropower planning should necessarily account for the potential non-stationarity of runoff under different climate futures, and consider the incidence of disruptions or temporal as well as structural declines in the production.

6.6. Conclusion

This paper developed a nexus framework for the energy-water-land nexus in SSA, and carried out an extensive screening of the most recent literature on the projected impacts of climate change on hydropower. These have been linked to the issues that a significant number of countries largely or entirely depend on hydropower generation and currently have little back-up options available, implying risks for supply reliability. Evidence from the literature pointed at a number of key facts. First, the state-of-the-art on climate-induced risks for power supply - and in particular on hydropower generation - finds heterogeneity in projected trends across the SSA region, while it also identifies some consistent trends at the regional level. Irrespective of uncertainty in the expected change of precipitation levels and patterns, different studies that adopted different methodologies seem to be rather consistent in pointing out that countries in East Africa could positively benefit from a warmer climate in terms of its hydropower output, while West and Southern Africa would be subject to negative impacts. Central Africa would be the least affected sub-region in terms of precipitation change and drought incidence. However, the magnitude of these changes displays large uncertainty ranges, sometimes covering positive as well as negative changes.

An observation of the relevant data shows that only some countries have successfully pursued a resilience-building strategy to prevent hydropower disruptions over the last three decades. Even in those countries, power mix diversification was however hitherto mostly based on natural gas, such as in Tanzania, the Republic of Congo, and Ghana. Other countries, including Malawi, Zambia, DR Congo, and Namibia, have remained entirely dependent on hydropower. Some virtuous examples of non-hydro RE-based diversification exist, such as Kenya, where significant capacity in geothermal and wind has been and will be added. At the same time, capacity expansions under development will lead to an even higher dependency on hydropower in Tanzania, Angola, Cameroon and Guinea, at least in the short term. An assessment of the long-run evolution of the SPEI48 index reveals that hitherto the frequency of drought events and the general dryness have evolved non-linearly and heterogeneously across the major river basins of SSA. Nonetheless, some of the major basins (i.e., the Niger, Nile, Sanaga, and Volta) have witnessed a significant drying. Current and future strategic energy decisions will thus have a major impact on the resilience of energy systems in SSA. Countries - in particular those highly reliant on hydropower - should plan the mix of capacity additions accordingly and increase adaptive capacity under extremes to safeguard energy security. A missed diversification may hinder economic growth prospects. The adoption of nexus approaches and modelling tools able to consider sectoral and transboundary interdependencies in dam planning are recommended. Furthermore, new dam management paradigms in complementarity with a large penetration of VRE must be developed, as they allow for a greater balancing, supply security, and sustainability.

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7. Summary and conclusions

This final chapter summarises the focal outcomes of the dissertation. It aims at providing some general conclusions based on the six essays considered. This is no simple task, because the dissertation is wide-ranging in scope: energy in sub-Saharan Africa is *per se* a broad topic, and so are the aspects inquired: electricity access, economic development and the nexus between the environment, energy, and human society. To perhaps ease the challenge, the chapter is structured into sub-sections.

First, the key research questions presented in Chapter 1 are restated and answered concisely. These first set of conclusions are specific to each essay. Secondly – in an attempt to “zoom out” and highlight some more general findings – the main insights and implications for policy that can be drawn from the empirical results of the dissertation are discussed. The general conclusions are presented based on their policy-relevancy. Already from its conceptualisation (and being a Doctoral Thesis submitted to a *School of Institutions and Policies*), this thesis has been focalised on delivering applied, policy-relevant pieces of analysis which can be informative for decision makers. Thirdly, being a data-intensive work, this dissertation provides novelties not only in terms of analytical results contributing to enriching the academic literature and policy insights, but also relatively to the methodologies developed and applied. Thus, in Section 7.3, an overview of the main methodological innovations found in the essays contained in the dissertation is offered.

Finally, the chapter concludes the dissertation highlighting the research pathways that might be pursued building on the work and methods here introduced. Several analytical insights are in fact still required to tackle the plethora of complex energy-related challenges in sub-Saharan Africa.

7.1. Key questions addressed and short summary of key answers identified

1- *How is the electricity access situation evolving in sub-Saharan Africa? Do official statistics provide a clear, realistic, complete picture of the situation? How might limitations in these statistics hinder effective policymaking? To what extent can satellite data complement or improve our understanding? What intrinsic limitation do they have?*

It is widely understood that energy poverty is still very diffused and persistent in sub-Saharan Africa. Yet, institutional statistics have struggled to capture the different dimensions of energy poverty and they have relied on rapidly outdated and unwieldy household surveys. In other words, even national governments struggle to have a comprehensive picture of energy access in their countries. This is because energy access is a complex challenge. It is sub-divided into different energy carriers and fuels (electricity, biomass, LPG, natural gas, kerosene, and so forth); different indicators (household access; consumption level; reliability of supply); and it can be measured at different levels (household and business activities connected to the grid; conditional on a village or city being reached by the grid; as a provincial statistics; including or excluding decentralised energy access solution). Providing a comprehensive picture of these multiple dimensions necessarily requires an integrated effort of public authorities, energy companies and citizens. It requires both a “boots-on-the-ground” view and a comprehensive picture from the authorities. Yet, in developing countries it is often the case that the bulk of the energy access deficit is concentrated in remote areas and public authorities struggle to keep pace with growing and moving populations or the uptake of decentralised energy access solutions to gain a comprehensive understanding of the energy access challenge.

To support the acquisition of this information in a quick, near-real-time updated, cheap way, I processed high-resolution population distribution maps (including demographic and migration trends), satellite-measured nighttime light, and settlement information. This allowed me to derive multi-dimensional (proxy) estimates of electricity access over space and time and compare them with a set of published records. My results are largely consistent with aggregated official statistics, but they reveal wide inequalities in the pace and quality of electrification, which cannot be observed in existing statistics. I observe that even in areas that formally have electricity access, power consumption is likely to be largely inadequate. I furthermore evidence the existence of a number of hotspots of electricity access and latent electricity consumption in sub-Saharan Africa, which I locate, distinguish by prevalent type of deficit, and for which I estimate the exposed population. Based on the recent progress that I observe through nighttime lights in the region, I calculate that the pace of electrification must more than triple to fulfil SDG 7.1.1 and discuss why electrification policy could fall short if aimed solely at boosting electricity connections.

Yet, I also argue that relying on satellite data alone to track electricity access is likely insufficient: firstly, it likely fails to detect electricity access in very sparse communities which rely on decentralised solutions capable of limited power provision; secondly, it may fail to distinguish among households with and without electricity in dense urban and peri-urban areas, where electricity access infrastructure is present and yet not all households are necessarily benefitting from electricity due to economic and social barriers. I however argue that when properly complemented and validated satellite-based methods have substantial potential in supporting communities and infrastructure detection and lower monitoring and energy access planning costs.

2- *Are the current limitations in energy demand formulation for electricity access planning playing a major role in the electrification strategy? What sectors might be the most important beyond the residential one? What could be the local microeconomic value added of the energy input to agriculture in currently unelectrified rural areas?*

The bulk of (geospatial) electrification planning models have so far been strongly supply-side (i.e. electricity provisioning technology) focused and have been calibrated based at best on regional average target demand level of residential electricity consumption for urban and rural consumers, with little within-country heterogeneity.

To contribute to the improvement of these tools and hopefully to enable a better and more comprehensive planning, I developed a data processing platform that based on a broad array of input data (most of which geospatial), scenarios, and equations, allows estimating the (potential, or latent) electricity demand across space (at different settlements of a country), time (at different hours of the day and months of the year) and – crucially – across a number of sectors beyond the residential one. Particular focus is put on the agricultural sector, because: 1) the bulk of the electricity access deficit in sub-Saharan Africa is found in rural areas; 2) the potential growth in agricultural productivity and therefore in local welfare from the input of electric energy is huge; 3) the analysis allows examining the nexus interactions between energy, water, food, and socio-economic development, a key pillar of this dissertation.

My assessment for the country-study of Kenya show that community, agricultural and productive uses – driven by the presence of farms, small businesses and commercial activities, healthcare facilities, and schools, – are important drivers of energy demand that need to be accounted for on top of residential demand in energy access infrastructure sizing and planning. The potential number and size of non-residential consumers in a community can in fact have a crucial effect on the total long-term energy demand, the peak loads, and consequently a direct effect on the optimal energy technology mix (diesel generator, PV, wind, biomass, hydro or hybrid technologies), on the optimal technology set-up (i.e. the choice between grid extension, mini-grid, or standalone solutions) and on the overall cost-benefit analysis of electrification. Moreover, a characterisation of the seasonal and hourly variation in the demand from different sectors is of crucial importance for properly planning the energy system and assessing the complementarity of variable renewable energy sources supply curves with the demand.

My findings suggest that a bottom-up approach to evaluating energy needs across space, time, and sectors is likely to improve the reliability and accuracy of supply-side electrification modelling and therefore of electrification planning and policy. I also estimate large potential farmer revenues (net of transportation and pumping costs) from the increased agricultural yield thanks to artificial irrigation rendered power by electrification.

3- *What are the implications of the lack of electricity access for thermal comfort at home of the people in sub-Saharan Africa? What are the electricity requirements to ensure a universal air circulation or cooling under different anthropogenic global warming scenarios? Does including the cooling energy needs on the top of baseline residential demand affect the optimal electrification planning in sub-Saharan Africa?*

Nearly one billion people live without electricity at home. Energy poverty hinders several autonomous adaptation actions, a key one being indoor thermal comfort decisions. It is therefore crucial that electricity infrastructure planning considers current and future air circulation and cooling (ACC) needs of energy-poor households on top of basic energy services. Without properly assessing these requirements, energy poverty might persist even after households get an electricity connection. At the same time, connecting to the previous essay, ACC services can become one of the first drivers of building energy demand in developing countries (and chiefly near the Equator). As a result, energy systems planning should explicitly account for these needs to deploy suitable infrastructure to avoid supply

I combine climate, satellite, and demographic data and scenarios to produce a global spatially-explicit estimate of unmet ACC demand due to the lack of electricity access. The results of my analysis show that providing universal electricity supply compatible with different ACC technologies adoption and use scenarios and a warmer climate requires significantly larger investments than under baseline targets and conditions. Moreover, when adding ACC-related energy needs on top of conservative demand targets, the optimal technology set-up shifts away considerably from decentralised energy access systems.

Planning universal household electrification without explicitly accounting for thermal comfort needs might therefore result in large energy supply deficits and persistent energy poverty even with nominal universal electrification. In turn, leaving millions of households with unmet (and growing) cooling demand could negatively affect the broader socio-economic development of low-income countries as a result of the negative repercussions on health (physical and mental) and productivity.

4- *What impact does governance quality have on the optimal electricity access investment strategy? Are private investors willing to invest in decentralised solutions in risky contexts, and what is the risk premium? Does, for this reason, the cost-optimal electrification strategy change compared to a conventional techno-economic analysis?*

Several previous studies in the literature have estimated that achieving universal electricity access in sub-Saharan Africa – a milestone of SDG 7 – requires about $30bn annually until 2030 on the top of baseline investment. The private sector plays a key role in supplying these investment flows, given the governmental budgetary constraints. Yet, companies face numerous sources of risk in their infrastructure investment decisions. This risk is usually factored in using a discount rate.

Yet, this risk has been so far poorly examined and accounted for in supply-side electricity access analysis. To allow for a more realistic evaluation of the role of the investment environment in financing energy access, here I introduce the Electricity Access Governance Index (EAGI), a composite index of energy sector regulatory quality, energy sector governance, and market risk. The index is implemented through a discount rate conversion into a bottom-up integrated electricity planning model (IMAGE-TIMER) to evaluate the role of different sources of risk for electrification investment dynamics.

The results show that the adoption of decentralised systems for achieving universal energy access requires governance and institutional reform to lower discount rates faced by investors and mobilise private finance. Failure to reform investment environments will likely hamper the uptake of decentralised systems even in areas where they would be the least-cost electrification option, and thus likely leave many without electricity.

5- *Will climate change adversely hydropower – the main generation technology in sub-Saharan Africa? How can the impact of hydroclimatic extremes on power systems reliability be measured in situations of data scarcity?*

In sub-Saharan Africa, 160 million grid-connected electricity consumers live in countries where hydropower accounts for over 50% of total power supply. A warmer climate with more frequent and intense extremes could result in supply reliability issues. To investigate this complex topic, I carried out a systematic review and analysis of the best available literature and data on hydropower, water levels, and droughts both for the past and for the medium-term future.

With my analysis, I find that only few countries have pursued a diversification strategy away from hydropower over the last three decades, while others' expansion plans will reinforce the dependency. This will occur irrespective of the fact that some of the largest river basins have experienced a significant drying during the last century. I find agreement on likely positive impacts of climate change on East Africa's hydropower potential, negative impacts in West and Southern Africa, and substantial uncertainty in Central Africa. Irrespective of the absolute change in gross technical potential, more frequent and intense extremes are projected.

I propose a possible paradigm to increase resilience and fulfil the pledges of the Paris Agreement: a synergetic planning and management of hydropower and variable renewables. According to this strategy, energy and water planners should together move to more flexible dam management strategies, where hydropower is not only a baseload technology but also a balancing solution for variable renewable energy integration. This may be a very meaningful prospect for promoting a low-carbon energy development in parts of SSA, as it could prevent a significant share of the uptake of gas and coal-fired thermal plants. The approach could also reduce the need for very large-scale hydropower schemes, which often are associated with substantial environmental and social impact.

7.2. Integration of non-conventional, spatially-disaggregated data into energy and development research

To the perception of the author of this dissertation, social sciences have traditionally privileged specific data types in empirical and forecasting analysis: institutional statistics, survey microdata, or systematic databases. The same goes for the energy modelling community, which still strongly underutilises available data that could allow improving the granularity, level of insights and accuracy of the analysis carried out. While on the one hand a partial justification is given by the computational intensiveness of handling geodatabases as opposed to conventional regional or country-level data, on the other it also stems from the lack of a good interconnection between the geospatial data analysis community (much more present in the environmental science field) and the social and sustainability science research. The use of data from sources that conventionally belong to other research fields, such as remotely sensed information on land, infrastructure or water has in fact only recently permeated the social scientific research.

While pioneering work highlighted this untapped potential (Blumberg and Jacobson, 1997), it was only in the last years that – partially thanks to the growing ease of access and processing of this data as a result of surging computational power and the release of tools and software that truly simplify the processing of this information (Gorelick et al., 2017) – that the use of this data is being consolidated in social scientific research fields. On the other hand, in the opinion of the author there is still a major under-exploitation of the potential of these data for hybrid hard scientific – social scientific research. The reasons include the lack of training in handling these data in most social scientific academic curricula and limited literature applying this data to social research.

In this dissertation, I have tried to advance the use of earth observation and big data to address hybrid social and hard science questions in compliance with what described by Li et al. (2020) as *geocomputation for social science*, namely '*an interdisciplinary approach combining remote sensing techniques, social science, and big data computation. Driven by the availability of spatially and temporally expansive big data, geocomputation for social science uses spatiotemporal statistical analyses to detect and analyse the interactions between human behaviour, the natural environment, and social activities' (p.0)*.

The thesis analyses energy in a developing continent from different perspectives. A key challenge I faced in my work is the need for georeferenced databases to examine the research questions and apply the models and calculations required to address the research questions, which is at odds with the (generally, but with some virtuous exceptions) scarcity of granular government and institutional data. Such shortage of data has been the driving factor behind the methodological advancement in spatial data processing and analysis that characterise different stages of this study.

Key geospatial and remotely-sensed data considered in this thesis include high-resolution population distribution maps (the HRSL and GHS suites); nighttime light radiance data from the NPP-VIIRS satellite sensor; statistically downscaled cropland extent and yield data; groundwater availability, depth, storage raster data; historical climate data and downscaled climate projections from CMIP experiment models; sub-national wealth distribution information; renewable energy potential maps (solar, wind, hydropower) and terrain information (land cover, slope); georeferenced facility and infrastructure data to enable bottom-up evaluations, such T&D power grid, roads, markets, hospitals and schools; satellite-measured time-series of water level at important reservoir basins.

In parallel with the data and to enable wrangling and collecting this multitude of information, my work has greatly benefitted from the large number of packages, tools, and algorithms that are being made available openly in the sphere of GIS data processing. Some of the instruments that found the largest employment in this study are QGIS processing algorithm and R packages *sf* (Pebesma, 2018) and *raster* (Hijmans et al., 2017), which together enable programmatically integrating geospatial data wrangling (both vector data as simple features and raster data) into research script that eventually lead to the core numerical and graphical conclusions highlighted in this dissertation.

In addition, many large-scale computations included in this thesis, such as continental scale high-resolution raster operations, would have been simply impossible without the use of Google Earth Engine, a free online cloud-computing platform for spatial data. I devote a special acknowledgment to Nick Gorelick and his research team at Google for making this instrument freely available for research over the last years. Examples of how this dissertation benefitted from GEE are the processing of nighttime lights; the grid-cell (30 meter resolution) population growth projection; the extraction of satellite-based climate data at specific sampling sites and region without the needs to download and process locally gigabytes of data; the assessment of accessibility to infrastructure.

7.3. Insights and implications for policy

Based on the findings of this dissertation, I recommend actions reported in Table 7.2 being considered or adopted. To each recommendation, I assign one or more target group number, as summarised in Table 7.1.

Table 7.1: Dictionary of the recommendation target groups and codes

Target group	Code
National governments of countries of sub-Saharan Africa	SSA_GOV
Interregional and international institutions	INST
Development banks	DEVBA
Foreign governments and governmental organisations	FOR_GOV
Businesses and practitioners in the energy and environment industry	BUSI_ENE
Academics and researchers	ACA
Civil society in sub-Saharan Africa	SSA_CS
Civil society elsewhere in the world	WORLD_CS

Table 7.2: Recommendations based on the results of this dissertation

#	Recommendation	Target groups	Cutting-edge literature	References to success stories and recent implementations in the direction of the recommendations	Steps forward required according to the author of this dissertation
1	Improving the measurement and reliability of data on energy access to enable better decisions and support investors.	SSA_GOV, INST, DEVBA, ACA	(Bhatia and Angelou, 2015; Culver, 2017; Monyei et al., 2018; Pachauri and Rao, 2020; Pelz et al., 2018; Samarakoon, 2019)	The World Bank, with support from the Energy Sector Management Assistance Program (ESMAP), has launched the *Global Survey on Energy Access*, using the Multi-Tier Framework (MTF) approach. The survey's objective is to provide more nuanced data on energy access, including access to electricity and cooking solutions. The MTF approach goes beyond the traditional binary measurement of energy access to capture the multidimensional nature of energy access and the vast range of technologies and sources that can provide energy access, while accounting for the wide differences in user experience.	The data collection is still at early stage, as raw data and statistics are hitherto only available for few countries. I recommend – like done in Chapter 2 of this dissertation – experimenting approach to use this high-quality, field-collected data for validating approaches that can approximate this information with higher time resolution, across broader geographical areas, and at a lower cost.
2	Accurately evaluating energy demand to enable productive, agricultural, social energy uses and promote socio-economic development.	SSA_GOV, INST, DEVBA, ACA, FOR_GOV, BUSI_ENE	(Burgess et al., 2020; Fabini et al., 2014; Falchetta et al., 2020; Kotikot et al., 2018; Kyriakarakos et al., 2020; Lee et al., 2016)	OXFAM engaged in the question of whether there are complementary policies that can be pursued in tandem with electrification to increase the likelihood of generating productive uses. Different initiatives from international organisation (primarily the World Bank's ESMAP and the UNDESA) fostered the consideration of the non-residential energy use in communities that still lack energy	Empirical evidence of the economic sustainability of large-scale decentralised energy systems must be conveyed to private companies to provide sufficient incentives to invest. The analysis in Chapter 3 of this thesis aims at supporting decision-makers in this direction. The techno-economic considerations need in fact to be supported by

				access. Recent focus has been put on the potential payback of investing in systems capable of powering productive, social, and agricultural uses of energy, as opposed to the conventional ‘*household electrification first’* paradigm.	robust policy and well-targeted subsidies. In general, the public spending in electrification must increasingly turn into an economic development investment in both spirit and scale of system provided. Sound regulation and governance must ensure the sustainability of the systems over time and their uptake.
3	Accounting for energy demand for climate change adaptation in the Global South, with specific attention to indoor thermal comfort and agricultural needs.	SSA_GOV, INST, DEVBA, ACA, FOR_GOV, BUSI_ENE	(Davide et al., 2019; De Cian et al., 2019; Mastrucci et al., 2019; Van Vliet et al., 2016; Wang et al., 2016)	The IEA recently released a seminal report on ‘*The Future of Cooling’* where the key importance in the present and ever more in the future of indoor air cooling and the consequences for energy demand and the environment are evaluated. The report puts special emphasis on the significance of adopting efficient cooling appliances and building techniques to reduce energy demand. The bulk of the future demand will stem from developing countries.	While globally the importance of cooling energy is increasingly being regarded by policymakers, it should also gain relevance in the agendas of energy and environment public decision makers of low and lower-middle income countries, as large fractions of the population will experience increasing distress and will demand more air circulation and cooling services. The assessment reported in Chapter 4 put this question at the core. Policymakers should set standards and regulation to ensure the uptake of efficient appliances to minimise social impact.
4	Evaluating and mitigating the risks perceived by private actors in the energy access investment field to unleash large-scale infrastructure development, in particular in decentralised systems.	SSA_GOV, INST, DEVBA, BUSI_ENE	(Eberhard and Gratwick, 2011; Rafique et al., 2019; Spyrou et al., 2019)	The *RISE (Regulatory Indicators for Sustainable Energy)* initiative promoted by the World Bank rates countries along a broad range of indicators to reflect a snapshot of a country’s policies and regulations in the energy sector, organized by the three pillars of the SEforAll initiative:	Regulatory assessment and tracking initiatives are an important source of information disclosure for private actors seeking new business opportunities and for governments to receive an external valuation of the sectoral situation in their country. Yet, this

				Energy Access, Energy Efficiency, and Renewable Energy. The assessment is regularly updated to keep track of country’s changing policy and regulatory framework and monitor improvements in investment attractiveness. The initiative contributes to informing players in the energy access sphere in the investment conditions of different countries.	information must be transferred at all levels to promote concrete investment: promoting efficiency and transparent competition; regulating the sector with a long-run perspective; minimising structural risks in the political, social, and financial spheres; allocating public spending and subsidies with equity and efficiency principles. Many SSA countries still face numerous gaps in this sense, and these often coincide with countries with modest performance in energy access and development indicators. Chapter 5 of this dissertation introduced an analysis to explicit the significance of these sources of risk for energy access investment.
5	Developing a new paradigm for managing and further developing hydropower potential in sub-Saharan Africa with the objective of increasing power sector resilience to climate change, co-optimising multiple water uses, and increasing the penetration of non-hydro renewables in the power mix.	SSA_GOV, INST, DEVBA, ACA, FOR_GOV, BUSI_ENE	(Deshmukh et al., 2018; Han et al., 2019; Sterl et al., 2020, 2018)	Recent pieces of research and reports by international organisation have highlighted the necessity to rethink the role of hydropower in sub-Saharan Africa. Currently the first generation technology in many countries but hampered by climate extreme events, and representing a very large source of untapped generation potential, hydropower management and planning should become resilient and minimise socio-environmental impact such as from mega-project. The dominant paradigm shift is that of implementing hydropower in	The topic of climate impacts on hydropower in SSA has been at the core of recent attention from both academic research and international organisations (e.g. IEA’s report *Climate Impacts on African Hydropower*). Also Chapter 6 of this thesis carried out an analysis of recent and future projected climate implications for SSA’s hydropower and propose a way forward. These analyses have evidenced potential risks in different areas and have paved the way to resilience-building

				complementarity with variable renewables and exploit it as a balancing generation technology, also in order to encourage the deployment of more moderately-sized plants and less invasive large schemes. It is also increasingly being acknowledged that hydropower potential exploitation should be planned with explicit consideration of the future climate in the basin and additional local sources of water withdrawal and consumption.	strategies. The challenge is now on the implementation side: hydropower should be considered jointly with other power generation technologies and other water uses when planned and developed. Moreover, the socio-environmental and transboundary impacts should be better accounted for to avoid conflicts like the ongoing Egypt-Ethiopia tension.
7	Integrating geospatial and earth observation data and GIS techniques into energy, economic and development research	ACA, DEVBA	(Li et al., 2020)	The growing field of “open” and programmatic GIS analysis, with the release of libraries in the most popular programming languages (also used by social scientists) and the release of online interfaces with large communities and support material to handle big geospatial data are increasingly permeating the social scientific research. Bottom-up energy modelling is a growing field, also thanks to the increasing computational power of personal computers and availability of disaggregated open data.	Traditional social scientific research and energy modelling still remain the predominant paradigms. Inclusion of GIS-based approaches and tools in university socio-economic curricula could increase, to the benefit of both hard and social-scientific communities. There is greater need to acknowledge the potential huge benefit of considering spatially-explicit data from academics, scientific journals, and policymakers – who should seek more geographically detailed results which would also enable them making better and more location-tailored decisions. The benefits of this paradigm are evident in most essays contained in this dissertation, which compare disaggregate result with the more limited level of insight that can be drawn with ‘conventional’ analysis.

8	**General conclusion 1:** integrating the nexus dimension into energy access strategies	All	(Falchetta et al., 2020; Kyriakarakos et al., 2020; World Resources Institute, 2020)	Recent evidence is showing that jointly planning energy systems and technological solutions that together can stimulate agricultural productivity growth might render electrification investment more economically attractive because of the significant reduction in the payback time of those investment. In turn, the increase in local revenues might provide a major spark to local socio-economic development. The key condition to enable this paradigm is the formulation of valuable business models.	See § 9.4.
9	**General conclusion 2:** increasing resilience to climate change in households, power system, agriculture sector, etc.	All	(Castells-Quintana et al., 2018; Cervigni et al., 2015; Conway et al., 2019; Sridharan et al., 2019)	While climate change mitigation has dominated the research and climate policy of the last two decades, recent reports (e.g. IPCC) are increasingly acknowledging that the impacts of climate change are already being experienced and they will harshen over the longer-run. As a consequence, adaptation and resilience building are gaining notable importance in research and international organisation narratives.	Developing countries governments – sustained by the international community and private actors, the key responsible players for the ongoing global environmental change – have the responsibility to embark in investment and policy measures that can help preventing future shocks on their population’s livelihoods.

7.4. Steps ahead and future research roadmap

According to the author, the key findings of this dissertation can contribute to highlighting a “master plan” for future research on energy, the nexus, and economic development in the context of sub-Saharan Africa. Namely, the study, assessment, and planning of the core challenges of energy access and of the water-energy-food-environment nexus as an integrated problem with integrated solutions.

Altogether this dissertation has attempted achieving some milestones for advancing such an integrated understanding. This intuition was neither clear to me from “day zero” nor it was presented in the initial research proposal. It materialized as I started inquiring into the (apparently) distinct topics at the core of the essays in this dissertation. Yet, research on these two topics has often followed two separated strands with little interactions.

Here below I present some aspects that explain the importance of future research on energy, economic, social and environmentally friendly development sub-Saharan Africa to look at these two major topics in an integrated fashion under the following starting points:

- Electricity access deficit is affecting mostly rural areas;
- 80% of agricultural production comes from small farmers, who however face constraints that reduce their productivity;
- Extensive rain-fed agriculture (90% of all cropland) under the unpredictable and erratic rainfall pattern has been the leading cause of the low productivity and food insecurity in Africa, together with a low degree of mechanisation;
- As a result of these factors, a poverty trap persists triggering cyclical famines and jeopardising local development opportunities;
- Climate change will have a very harsh impact on agriculture while also affecting the density and quality of nutrients in plants;
- Growing resources demand and changing consumption patterns (mostly in urban areas) will trigger increasing pressure on environmental flows and stress of environmental quality, mainly in rural areas;
- Planning water and agricultural solutions such as water pumping, crop processing, and fertilisation requires the input of energy;
- Energy access is a fundamental requirement for sustainable food cooking.
- And so forth…

To address these major challenges, there is a need for an integrated evaluation of infrastructure planning, policy making, and investment. For instance, access to affordable energy enables pumping groundwater, rainwater harvested and stored in underground or surface storage tanks, and powering machineries that could significantly contribute in closing the yield gap. This would have positive consequences for food security (SDG 2), ensuring healthy life (SDG 3), ensuring equitable and inclusive education (SDG 4), access to water (SDG 6), access to energy (SDG 7) and local socio-economic development (SDG 8), thus contributing to the reduction of rural-urban and gender inequalities (SDG 10). The impact of rural energy access projects is already being experienced in many poor communities across Africa as private decentralised energy access companies see increasing demand as a result of falling technology costs and more refined business models.

Future research should put together specialists who are pioneers in nexus integrated modelling and in developing commercial business models in these emerging markets. These research projects should aim at developing support tools that facilitate and streamline some of the hardest and most costly processes in the implementation of energy access and nexus business models, such as the process of site selection and technology evaluation. Useful tools to address this challenge include platforms integrating existing bottom-up solutions with regional and basin-scale. The modelling research should however necessarily be complemented by an extensive assessment of financing, governance, and policy mechanisms that can enable the identified solutions. This is crucial for the macro, national government-level regulatory perspective, via the energy access funding and investment landscape to the very micro validation of community-level business models. From design, through development, validation and implementation future work should also be guided by the core principle of commercial relevance.

These intuitions, namely integrating energy access, nexus, and development research and combining modelling with business and policy research – is reflected by very recent contributions such as Kyriakarakos et al. (2020) or World Resources Institute (2020). The authors of these contributions namely highlight the need to *“focus on gathering data to get a realistic picture of small-scale demand and placing development-oriented service delivery organizations at the center of the solution”* and they show that *“agriculture related businesses [can] take the lead in the electrification activities of the surrounding communities. It is shown that the high cost of rural electrification can be met through the increased value of locally produced products, and cross-subsidization can take place in order to decrease the cost of household electrification”.*

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Appendixes

Appendix to Essay 1

Figure A1.1 plots a map of Tanzania highlighting the position of the mini-grids. Of the 107 facilities reported in the country, our satellite-based approach can detect 78, i.e. 73%. Irrespective of the limited geographical scope of this dataset, the observation of nighttime light radiance in the proximity of the geographical coordinates where the mini-grid is reported to be installed can be considered a direct empirical confirmation of the successful detection of most mini-grid solutions. In turn, this result provides an interpretative guideline of our electricity access estimates. Namely, it suggests that the estimates are broadly inclusive of populations served by mini-grid facilities. As a result, any residual discrepancy with the official statistics can be attributed to a narrower set of causes, namely: (i) the failed detection of standalone household-level generation solutions by nighttime lights; (ii) the 450-meter resolution of the nighttime light data and the underlying assumption that in each pixel where electricity use exists everyone is benefitting from electricity access; (iii) biases and statistical growth in the official statistics. As discussed in greater detail in the main paper, questions of the definition of electricity access must be raised.

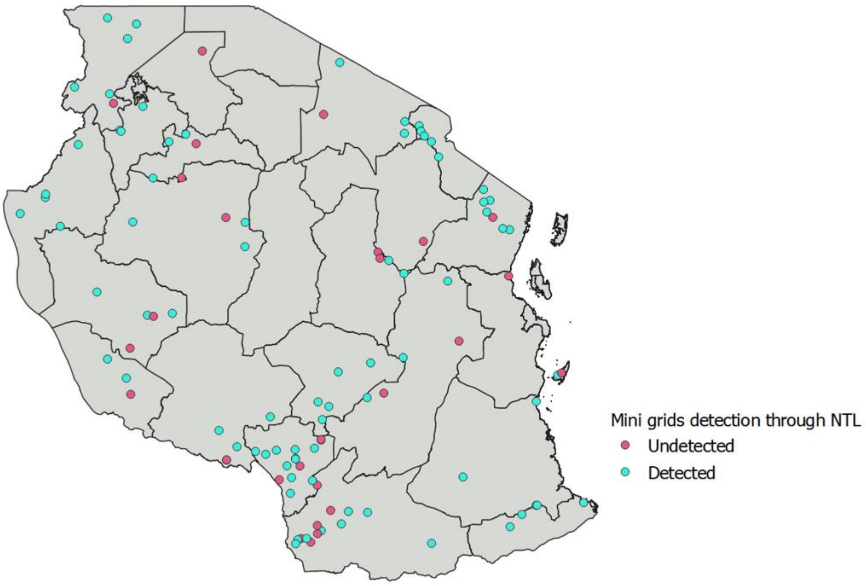

***Figure A1.1:** Map reporting the effectiveness of the nighttime light-based methodology to detect operational mini-grid systems in Tanzania.*

Figure A1.2 shows a line plot – by country – of the electrification levels reported by the *Tracking SDG7: The Energy Progress Report 2019* (ref. 2). It reveals that a large number of countries seem to have kept quasi-linear changes in their reported electricity access level. Testing this hypothesis in a regression framework yields to a highly significance of the linear time trend (at a 1% level), but conversely it points to a rejection of the existence of a quadratic or cubic time trend at a 5% level of statistical significance.

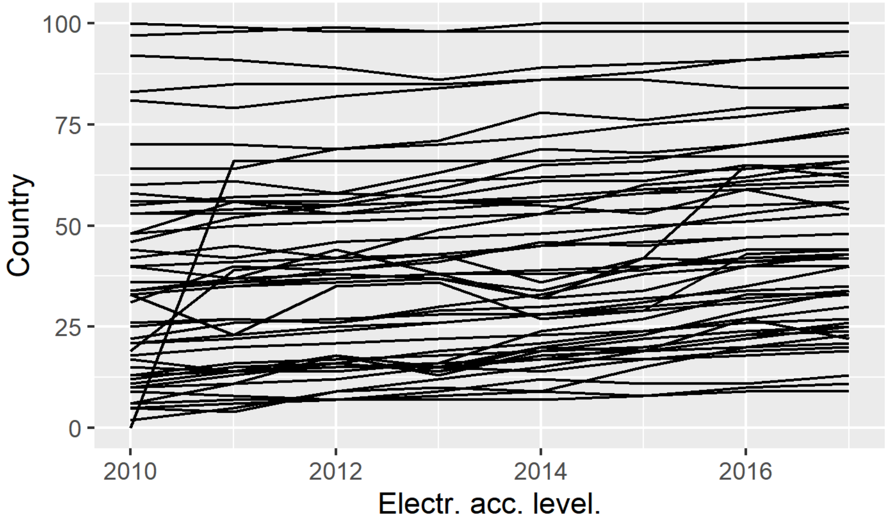

Figure A1.2: *Electricity access level progress (2010-2017) according to the database of the Tracking SDG7 report database (ref.* [2]*).*

Table A1.1: *DHS surveys data regression results*

	Dependent variable:						
	Electr. access level 2019	Elect. progress 2014-2019	Average access tier	`TV ownership	`Refrigerator ownershup	Mobile telephone ownership	Radio ownership
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**
Wealth distribution: Gini coefficient	-1.463***	0.093***	-4.790***				
	(0.142)	(0.034)	(0.483)				
Average access tier				19.823***	13.181***	10.054***	6.812***
				(0.923)	(0.681)	(0.830)	(0.745)
Constant	1.045***	-0.020	2.588***	20.924***	11.405***	46.493***	38.608***
	(0.067)	(0.016)	(0.226)	(2.843)	(2.098)	(2.557)	(2.293)
Observations	188	188	188	216	216	216	216
R^2	0.579	0.412	0.464	0.828	0.780	0.780	0.670
Adjusted R^2	0.542	0.361	0.418	0.814	0.762	0.762	0.643
Residual Std. Error	0.194 (df = 172)	0.047 (df = 172)	0.659 (df = 172)	10.257 (df = 199)	7.570 (df = 199)	9.225 (df = 199)	8.274 (df = 199)
F Statistic	15.776*** (df = 15; 172)	8.040*** (df = 15; 172)	9.945*** (df = 15; 172)	59.987*** (df = 16; 199)	44.016*** (df = 16; 199)	43.988*** (df = 16; 199)	25.236*** (df = 16; 199)
Country fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: *p<0.1; **p<0.05; ***p<0.01

Table A1.2: *ISO3– country names codebook*

ISO3	Country name
AGO	Angola
BDI	Burundi
BEN	Benin
BFA	Burkina Faso
BWA	Botswana
CAF	Central African Republic
CIV	Côte d'Ivoire
CMR	Cameroon
COD	Congo (Dem. Rep. of)
COG	Congo (Rep. of)
ERI	Eritrea
ETH	Ethiopia
GAB	Gabon
GHA	Ghana
GIN	Guinea
GMB	Gambia
GNB	Guinea-Bissau
GNQ	Equatorial Guinea
KEN	Kenya
LBR	Liberia
LSO	Lesotho
MDG	Madagascar
MLI	Mali
MOZ	Mozambique
MRT	Mauritania
MWI	Malawi
NAM	Namibia
NER	Niger
NGA	Nigeria
RWA	Rwanda
SDN	Sudan
SEN	Senegal
SLE	Sierra Leone
SOM	Somalia
SSD	South Sudan
SWZ	Swaziland
TCD	Chad
TGO	Togo
TZA	Tanzania (United Rep. of)

UGA	Uganda
ZAF	South Africa
ZMB	Zambia
ZWE	Zimbabwe

Table A1.3: Datasets used in the modelling framework

Dataset	Unit	Source	Time step	Spatial resolution
High-resolution settlement layer	People	Ref. [3]	1 year	30 m
Global Human Settlement Layer – built up areas and settlement type layers	Class	Ref. [4]	5 years	250 m
VIIRS-DNB nighttime light radiance	$\mu W \cdot cm^{-2} \cdot sr^{-1}$	Ref. [5]	1 month	450 m
GADM shapefile	-	Ref. [6]	-	-
DHS surveys	% of people with access	Ref. [7]	Multiple years	Province-level
IEA Energy Access database	% of people with access	Ref. [8]	1 year	Country-level
Tracking SDG7: The Energy Progress Report database	% of people with access	Ref. [9]	1 year	Country-level
Atlas of the Sustainable Development Goals from World Development Indicators database	% of people with access	Ref. [10]	1 year	Country-level
ESMAP Multi-tier Framework Surveys	kWh/household/year	Ref. [11]	1-2 years	Household-level

Supplemental References to Essay 1

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Appendix to Essay 2

Detailed materials and methods

Population settlements clustering

Population clusters are generated based on a processing algorithm which takes a gridded population raster layer as the main input and generates polygonal shapes as outputs. Previous applications of a similar approach are provided in refs. (Arderne, 2020; *KTH-dESA/PopCluster*, 2019). The algorithm selects high population density raster pixels (with a pop. >10 inhabitants / 900 m^2 ≈ 1,110 inhabitants / km^2) and classifies them as 'core'. The core pixels are converted to polygons and buffered by a 1 km radius to unify surrounding cores. The centroids of the resulting polygons are then extracted to identify a unique core for multi-core population areas. Finally, Voronoi polygons (the boundaries of the area closer to a given centroid than to any other centroid) are generated to cover the entire regional surface and include periphery and non-urban areas (e.g. cropland) within the reference polygon for each core centroid. The methodology allows grouping populations into boundaries that are heterogeneous in size and shape while collecting a set of neighbourhooding buildings and land. The algorithm is summarised in Figure A2.1.

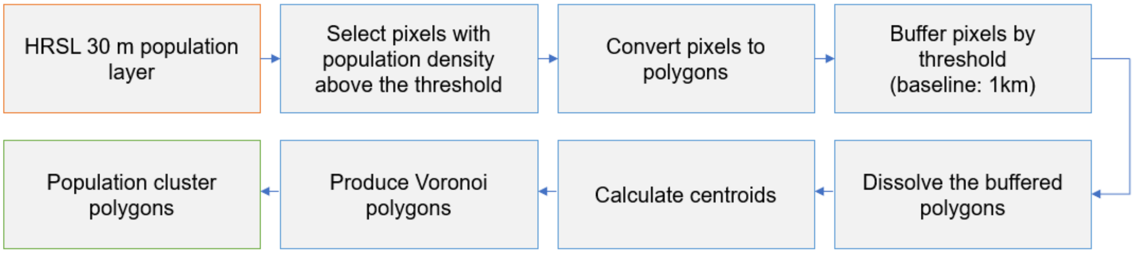


Figure A2.1: *Schematic framework of the GIS algorithm to generate population clusters. The clusters represent the functional units of the GIS data processing and the demand nodes of the assessment.*

In this study, the High Resolution Settlement Layer (Facebook Connectivity Lab and Center for International Earth Science Information Network - CIESIN - Columbia University, 2016) dataset, providing population counts at a 30 m resolution based on statistical downscaling of census population based on a broad array of remotely-sensed datasets, is used. The High Resolution Settlement Layer is based on the 2015 census. Therefore, we estimate the change in the population of each grid cell from 2015 up to 2020 by applying the yearly country-level population growth rate and the share of urban population (ref. (The World Bank, 2019)). Algebraically, the union raster layer (U) of the urban and rural population's layers in year *t* is expressed by:

$$Pop_{\mathrm{t}}^{\mathrm{i}} = U\left(Pop_{\mathrm{t-1}}^{i\,urb}\left(1 + PGR_t^c(1 + \Delta URB_{t-1}^{t\,c})\right), Pop_{\mathrm{t-1}}^{i\,rur}\left(1 + PGR_t^c(1 + \Delta RUR_{t-1}^{t\,c})\right)\right)$$

(Eq. A2.1)

where:

- $Pop_{\mathrm{t}}^{\mathrm{i}}$: the population in each cell (i) in year t
- PGR_t^c: population growth rate in country c at year t

$\Delta URB_{t-1}^{t\,c}$increase of share of Urban population at year t respect to previous year in country c

- $\Delta \mathrm{R}UR_{t-1}^{t\,c}$increase of share of Urban population at year t respect to previous year in country c

The rescaling (Eq. A2.1) allows to integrate the heterogeneity in the demographic change across urban and rural areas and across each country. The main limitation in this approach is that – within each country – population dynamics are homogeneous across all urban and rural areas, taking the national value of the official statistics from the World Bank (The World Bank, 2019).

Urban and rural settlements are identified at the grid-cell level using the 'degree of urbanization' method that delineates and classify settlement typologies via a logic of population size, population and built-up area densities and contiguity of the cells (A.J. et al., 2019). In our study the populations cells are classified as urban for contiguous cells with a density of 1,500 inhabitants per km^2 and a minimum of population of 5,000 inhabitants (GHS-SMOD≥2), as rural when grid cell are outside the urban clusters (GHS-SMOD≤1), or as not inhabited (GHS-POP=0). To conclude, the total population living inside each cluster is calculated with a zonal statistics algorithm (i.e. as the sum of the raster pixels falling within the polygon boundary).

Residential electricity demand

Residential demand of rural and urban households in Kenya, both divided into five tiers of consumption, is computed by estimating electric appliances ownership across different tiers of consumers. The baskets of appliances are obtained through a literature review (ref. (Adeoye and Spataru, 2019; Blodgett et al., 2017; Kotikot et al., 2018; Lee et al., 2016; Monyei et al., 2019; Monyei and Adewumi, 2017; Sprei, 2002; Thom, 2000)) supported by the authors' personal experience. The compiled database is reported in **Supplementary File F2.1**, where every category of users is characterized by a corresponding usage pattern of the owned appliances, differentiating every month to account for seasonality of the uses. Subsequently, the stochastic bottom-up tool RAMP (Lombardi et al., 2019) is employed to compute the load curve of each household type for each day of the year at a 1 minute time resolution. In order to avoid overlap of the peaks in this process, the simulation of the load of each tier is carried out for 100 households, taking advantage of the stochastic characteristic of RAMP, which avoids that the use of the same appliance coincides (deterministically) among users of the same category.

Allocation of population to residential consumption tiers

The next key methodological challenge requires allocating the simulated residential energy demand load curves of each household type to the population without electricity access in each cluster.

Firstly, a multi-variate random forest regression machine learning model is estimated to evaluate the current association between the distribution across tiers of households who already benefit from electricity access and their characteristics throughout sub-Saharan Africa:

$$Tiershare_i = WQ, UR, \rho_i + \epsilon_i$$

(Eq. A2.2)

where:

- $Tiershare_i$ is a vector of the shares of population with access in each cluster *i* that belongs to each of the four access tiers. Information about the current distribution of households with electricity access across tiers is derived from ref. (Falchetta et al., 2019). This source provides satellite-proxied field-validated estimates of the distribution of households with electricity access across tiers;
- WQ is a vector of five variables expressing the proportion of households in each wealth quintile in the province within which each cluster falls. The sum of the five variables at each cluster is thus always 1. The wealth distribution information is derived from the most recent DHS survey data for each country (USAID, 2009);
- UR is a fractional variable expressing the share of the population in each cluster that is classified as urban; it is calculated based on the ‘degree of urbanization’ method (A.J. et al., 2019);
- ρ_i is a vector of country fixed-effects;
- ϵ_i is a vector of residuals.

The trained model is then used to predict the propensity of households are currently without access to electricity to fall within each of the five electricity tiers once they gain electricity access. To conclude, the predicted distribution of households without electricity across energy access tiers in each cluster are matched to the corresponding load curves and the relative power consumption levels estimated in

RAMP. The approach ensures that in each cluster the latent residential electricity demand depends on the current link between electricity access tiers, wealth distribution, and urban/rural prevalence within each country. The results of the regression model are reported in Table A2.3.

Healthcare and education demand

In order to assess the energy behaviour of primary schools and healthcare facilities in Kenya, a field campaign was conducted in the second semester of 2019 by the authors and their team with the specific purpose of interviewing personnel from public facilities about their appliance ownership and usage patterns. During this campaign 65 Primary Schools, 10 Dispensaries (Tier 1), 14 Health Centres (Tier 2) and 3 Sub-County Hospitals (Tier 3) were visited. The purpose of the field campaign was double, collecting data directly from the facility managers to better model the electrical loads and engage with local authorities to better understand and classify the different kinds of facilities into Tiers, ad understand the national plans for the public facilities in the medium term. Thanks to the field campaign it was hence possible to collect and process the data presented in **Supplementary File F2.2**. The reported data are then fed into the open source tool RAMP (Lombardi et al., 2019) that thanks to a stochastic bottom-up process computes the load curve of the user per each day of a year, with a one minute time resolution.

The generated load profiles are then parsed to geospatial information about the location and characteristics of healthcare and education facilities in Kenya with the following logic:

Healthcare

- Tier 1 -> dispensary; Tier 2 -> Health clinics; Tier 3 -> Sub-district hospital; Tier 4 -> District Hospital / Provincial General Hospital; Tier 5 -> National Referral Hospital
- Facilities with missing beds number: Tier 1 -> 0; Tier 2 -> 45; Tier 3 -> 150; Tier 4 -> 450; Tier 5 -> 2000
- Number of beds in healthcare facility *i* of tier *k* * per-bed load at tier *k*

Education

Number of pupils in school *i* * per-pupil load

Micro-enterprises and commercial activities demand

In the M-LED framework, we estimate the electricity demand induced by small-scale productive and commercial activities that are widely emerging in communities of sub-Saharan Africa with an availability of electric energy, such as barber shops, minimarkets, or telecommunication points. This is carried out in three steps. First, a composite index based on the productive activities drivers and energy use is constructed based on road density (with road infrastructure data drawn from ref. (Center for International Earth Science Information Network - CIESIN - Columbia University and Information Technology Outreach Services - ITOS - University of Georgia, 2013)), employment levels and wealth distribution (at the provincial level, with data from ref. (USAID, 2009)), and city accessibility (ref. (Weiss et al., 2018)) proximity is built. The indicators are aggregated using a principal component analysis (PCA). PCA is a multivariate statistical method that is used in development research to reduce the number of variables in a dataset and construct composite indices. In a PCA, the variables are weighted according to the variance explained by the first principal component (Booysen, 2002). Figure A2.2 below highlights the results of the PCA:

***Figure A2.2:** Results of the PCA to evaluate the propensity of micro-entrepreneurial and commercial activities to operate*

Next, the PCA outcome is rescaled to the 0.3 and 0.6 range (following (Moner-Girona et al., 2019)) to create a bottom-up mark-up factor on top of the residential demand. The baseline load curve (share of demand at each hour of the day over the total daily demand) of micro productive activities is assumed to follow the same path of that described in (Moner-Girona et al., 2019), which in turn relies on ground-metered data from mini-grids in Kenya. Finally, a seasonal variation is imposed to the monthly demand loads curves: in particular, the seasonality follows the same monthly mark-up observed in the residential demand across months of the year.

Algebraically, the final sectoral demand $CommProd_{imh}$ (where *i*, *m*, and *h*, identify demand clusters, months of the year, and hours of the day, respectively) is expressed as:

$$CommProd_{imh} = (1 + PCA_i^{range}) \times Residential_{imh} \times CommProdCurve_{mh}$$

(Eq. A2.3)

where:

- $CommProd_{imh}$ is the commercial and productive demand at each cluster *i* at each month of the year *m* at each hour *h*;
- PCA_i^{range} is the result of the PCA at each cluster rescaled to the 0.3-0.6 range;
- $Residential_{imh}$ is the residential demand at each cluster *i* at each month of the year *m* at each hour *h*;
- $CommProdCurve_{mh}$ are the twelve month-specific hourly curves for the sectoral demand derived from (Moner-Girona et al., 2019) and adjusted for the seasonality based on the residential seasonality variation.

Irrigation water requirements modelling

In developing countries crops are mostly rain-fed and existing water storage systems exploit gravity. For instance, in sub-Saharan Africa it is estimated that over 90% of all agricultural land is rain-fed only (Rockstrom et al., 2007). The possibility to exploit electrical energy to pump water bears a huge rural productivity growth potential – if those water resources are used sustainably (Jägermeyr et al., 2016; Mueller et al., 2012). Thus, accurately predicting those water requirements and their load curve and in turn derive the electric energy necessary to pump it can shed light on the role of pumping energy in the elaboration of a rural electrification plan that might act as a trigger to rural productivity growth.

We exploit 30-m resolution GIS information on the location of rainfed cropland in Africa (Teluguntla et al., 2018) to statistically downscale 10 km resolution information on the cropping area and regime of 42 distinct crops (You et al., 2014a). First, we use the GFSAD30AFCE cropland extent product to estimate the rainfed cropland area within each cluster. Then, using the MapSPAM database and referring to the rainfed harvested (i.e. not only the physical area, but the total area accounting for multiple harvests of a crop on the same plot) cropland area for 42 types of crops, we calculate the total area for each crop type within the clusters. Since, however, the GFSAD30AFCE product has a 30 m resolution while the

MapSPAM layers only have a 10 km resolution, we redistribute the area value written into each 1 km resolution pixel such that it is proportional to the share of total cropland area within each cluster over the total cropland area underlying each MapSPAM pixel. Following this approach, we are able to downscale the layers based on the 30 m layer, under the assumption that, under each 10 km pixel, for each crop cropland is homogeneously distributed in underlying pixels. While this is an assumption, it is not particularly limiting given the already high resolution of the MapSPAM layer, which limits the maximum spatial allocation error to a ~ 500 m radius, and in any case is such that the total sum of cropland in the clusters underlying the MapSPAM pixels is equal to the value reported in the MapSPAM pixel itself.

We then combine the cropland information with satellite-derived observations of precipitations and evapotranspiration (Abatzoglou et al., 2018) and information about crop scheduling and watering periods (refer to Table A2.2) to accurately estimate the daily water gap that would be necessary to ensure the optimal yield is achieved in each cluster (with the caveat that we do not consider variation in fertilisation, pesticides, or land management regimes):

$$WR_i^y = \sum_m^{12} \frac{AET_i^m - PR_i^m \, \eta \, CRSHARE_i}{\eta_c}$$

(Eq. A2.4)

where:

- WR_i^y is the yearly irrigation water requirement at cluster *I;*
- AET_i^m is the total monthly actual evapotranspiration in cluster *i* calculated from the processed geospatial information on each crop's harvested area (You et al., 2014b), the relative crop factors (Allen et al., 1998) – which depend both on each specific crop and the agroclimatic zone where it is being cultivated –, and the local potential evapotranspiration (Abatzoglou et al., 2018);
- PR_i^m are the monthly cumulative precipitations;
- $CRSHARE_i$ is the share of cropland area over the total cluster area;
- η is a roots absorption efficiency parameter, set at 0.6.

The artificial irrigation water requirement is increased by dividing it by an irrigation efficiency parameter η_c. This is crop-specific, as each crop is irrigated with either drip, sprinkler, or surface irrigation, for which efficiencies of 0.85, 0.6, and 0.6, respectively, are assumed. Each crop is allocated to a technology following the FAO guidelines (Allen et al., 1998), with staple crops allocated to surface irrigation, and sprinkler and drip irrigation to vegetables and sugarcane and fruit trees, respectively. Rainfall is given an absorption efficiency of 0.6. Finally, the yearly water requirement per hectare per crop is embedded into each cluster, a weighted sum between the products of such water requirement and the rainfed harvested area of each crop in that cluster is calculated. This results in monthly and yearly water requirement in m^3 within each cluster, which is the requirement necessary to attain the potential yield in currently rainfed cropland.

Water pumping energy demand quantification

To quantify the electricity necessary yearly to satisfy the estimated demand for irrigation in each cluster, we set-up a groundwater pumping model based on Eq. SI5:

$$PW_i = \frac{\rho q g h}{\eta}$$

(Eq. A2.5)

where

- PW is the hydraulic power requirement in W;
- ρ is the density of the fluid in $kg \cdot m^{-3}$ (here set at 1,000, for water);
- q is flow capacity of the pump in $m^3 \cdot h^{-1}$;
- g is the gravitational constant (9.81 $m \cdot s^{-2}$) ;
- h is the differential head, in m;
- η is a pumping efficiency parameter, set at 0.75.
- h is defined by calculating the average local groundwater well depth using data from MacDonald et al. (2012) – including depth, storage, and productivity.

The flow capacity of the pump q is defined as the flow capacity necessary to satisfy the local irrigation requirements in the month t with the highest requirement assuming a maximum watering of six hours per day. To translate the pumping power requirement (W) in the daily electricity demand (kWh), the following product is estimated:

$$PWh_m = \frac{PW}{1000} \times IH_m$$

(Eq. A2.6)

where:

- PWh_m is the estimated electricity consumption of the pump (in kWh) in each month *m;*

- PW is the nameplate power of the pump (in W);
- IH_m are the number of irrigation hours in month *m.*

Finally, as shown in Figure A2.3, to derive cluster and month-specific load curves we consider an archetypical curve with two irrigation windows per day (5am-9am and 10pm-12am) where the pump is operating, consistent with farming practices to reduce evapotranspiration:

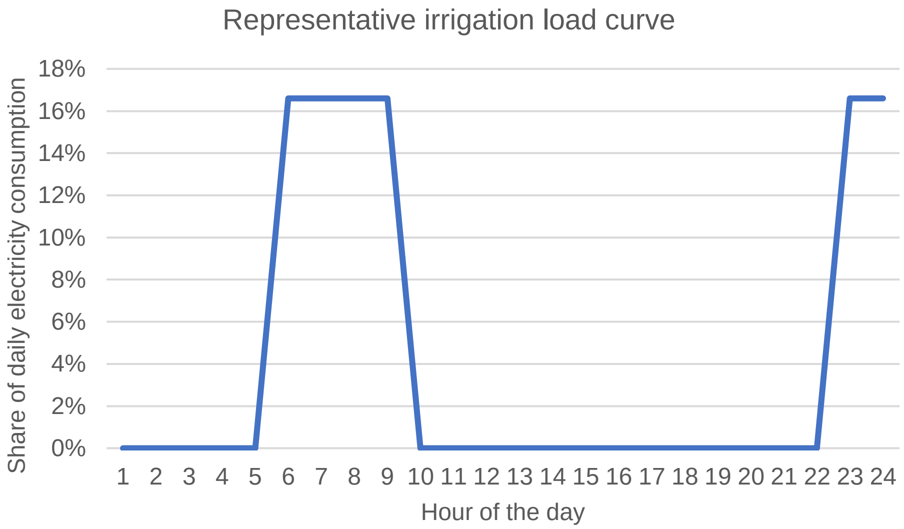


Figure A2.3: *Representative load curve of the irrigation electricity demand (% of daily load at each hour of the day).*

In order to guarantee a sustainable supply of irrigation water, two constraints are set so that irrigation does not lead to the dwell's depletion.

The constraints are formulated as:

$$WW_i^d \leq \frac{\left(GWProd_i * \frac{Noirrhours}{Irrhours}\right) + GWProd_i}{1000}$$

(Eq. A2.7a)

and

$$WW_i^d \leq \frac{GWStor_i}{Irrhours \times 3600} + \frac{GWProd_i}{1000}$$

(Eq. A2.7b)

where:

- WW_i^d is water withdrawal for irrigation purposes on the day of the year *d* in cluster *I;*
- $GWProd_i$ is the average groundwater dwell productivity (in litres per second)*;*
- $GWStor_i$ is the average groundwater dwell storage (in meters)*;*
- $Irrhours$ and $Noirrhours$ are the number of hours in which the pump is operated or not, respectively, during the average irrigation day.

If the constraints are not met, the algorithm seeks to fill the watering gap withdrawing from the nearest freshwater surface (if this is within a reasonable distance threshold, set at 5 km). The surface water pumping is modelled as:

$$SFPW_i = q^i \times \frac{(32 \times WS \times SWD_i \times V)}{PD^2} \times \eta^{-1}$$

(Eq. A2.8)

where:

- $SFPW_i$ is the power of the surface water pump in W
- q^i is the required water flow rate (m^3/s), obtained as the difference between the total required flow rate to meet irrigation needs and the flow rate that can be guaranteed sustainably by the groundwater pump;
- WS is the speed of water in the pipe, set at 2 m/s;
- SWD_i is the Euclidean distance to the surface water body;
- V is the viscosity of water, 0.00089 Ns/m^2
- PD is the pipe diameter, set at 0.8 m
- η is a pumping efficiency parameter, set at 0.75.

In those instances where the irrigation demand cannot be fulfilled sustainable either by groundwater or via surface water pumping, a remark is signalled in the analysis result about the possibility to replace the existing crops or cropping schedule to relax the water stress in critical clusters. The analysis is carried out at a daily temporal resolution to account for overlapping growing seasons of crops found in each cluster and the therefore greater simultaneous water withdrawal needs.

Crop processing electricity demand

To estimate the electricity necessary to mechanically process the raw crop production of each cluster, an extensive literature review of crop processing energy requirements in the context of developing countries is carried out. Refer to **Supplementary File 2.3** for an extensive summary of the sources accessed. Figure

SI4 summarises the resulting estimates range for each crop (in kWh/kg of processed crop).

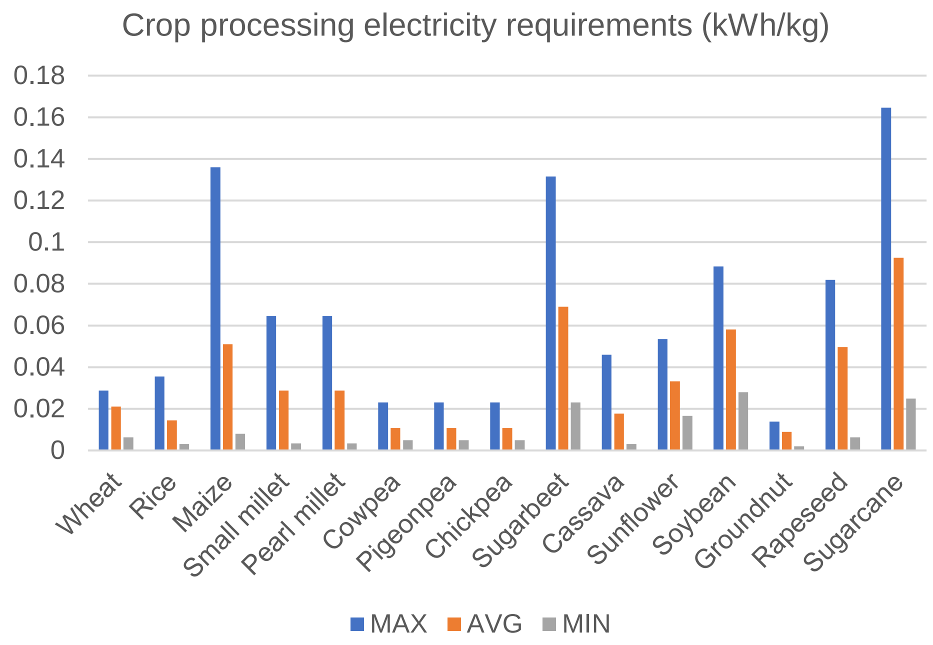


Figure A2.4: *Comparison of the literature ranges for crop processing electrical requirements for the main crops considered for sub-Saharan Africa (in kWh/kg of processed crop).*

Thereafter, the yearly crop yield in each cluster *i* for each of the 42 crop classes *c* of the MapSpam database is estimated multiplying the mean crop yield (in kg/ha) of pixels falling into each cluster with the downscaled crop-specific cropland extent (in ha) of each cluster.

$$YYield_c^{im} = \overline{Y\iota eld_c^{im}} \times cropland_c^i$$

(Eq. A2.9)

where:

- $YYield_c^{im}$ is the yield of each crop *c* at each month *m* in each cluster *I;*
- $\overline{Y\iota eld_c^{i}}$ is the average yield (in kg/ha) of crop c for cropland falling within each cluster *I*;
- $cropland_c^i$ is the harvested area of each crop *c* at each cluster *I* (in ha).

The total yearly electricity consumption for crop processing (*CP*) in each cluster is then calculated as:

$$CP_{im} = \sum_{i}^{N} YYield_c^{im} \times kWh/kg_c$$

(Eq. A2.10)

where:

- CP_{im} is the estimated electricity consumption for crop processing (in kWh) in each month *m* at each cluster *i;*
- $YYield_c^{im}$ is the yield of each crop *c* at each month *m* in each cluster *I;*
- kWh/kg_c are the crop-specific unit processing energy requirements (in kWh).

In a similar fashion to the irrigation load curve definition, crop processing machinery follows an archetypical load (Figure A2.5) with an on/off flat curve and an operation window between :

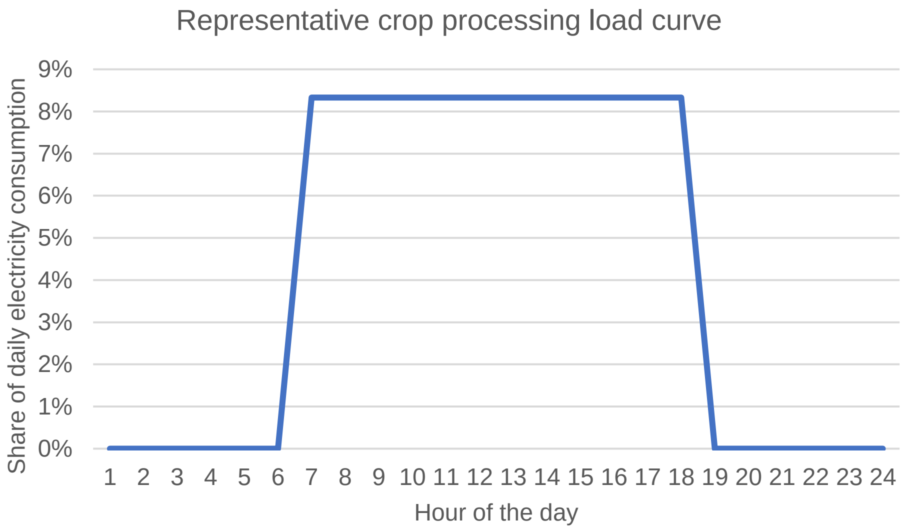


***Figure A2.5:** Representative load curve of the crop processing electricity demand (% of daily load at each hour of the day).*

Yield gap. agricultural revenues, and costs

For the Kenya country-study, we estimate the local productivity ($kg \cdot ha^{-1}$), the mean yield for each crop is calculated using the MapSPAM rainfed crops layers. The total production in rainfed cropland is the given by the product of yield and harvested area in each cluster. To estimate the revenues stemming from the irrigation of previously rainfed cropland and the related costs, we develop a simple model of production, transportation, and wholesale. Farmers in cluster *i* would bear cost components *F* (the fixed cost for purchasing the water pump) and *R* (the running costs, including electricity to power the pump and operation and maintenance of the appliance), as well as *T* (the travel costs to the closest wholesale market, including the rent/use of the truck, the fuel, and the opportunity cost of time). In turn, they earn a revenue which is defined as the additional yield of each crop produced thanks to irrigation by the wholesale market price at which that crop is currently exchanged (according to official statistics).

Here we model transportation costs, total pumping costs, and the potential revenues from wholesale to quantify the potential locally generated agricultural revenues from the increased agricultural productivity as a result of the artificial watering. To estimate this added value, we retrieve the most recent database of wholesale prices for a large basket of crops in Kenya relative the location of each wholesale market. We then calculate what is the nearest wholesale market to each cluster, and – assuming constant prices over time – we estimate the yearly revenue.

$$Revenues_i = \sum_{j=1}^{C} P_i^j \times Yieldgap_i^{jc}$$

(Eq. A2.11)

where:

- P_i^j is the local (i.e. in each cluster *i*) wholesale unit price for each crop *j*
- $Yieldgap_i^{jc}$ is the average difference between rainfed and irrigated yield in climate zone *c* for each crop *j.*
- To estimate and subtract transportation costs needed to generate these revenues to obtain effective profit, we calculate the following:

$$TCs_i = 2 \times (TTM_i \times Fuelcost_i \times lpermin) \times n$$

(Eq. A2.12)

where:

- TTM_i is the travel time from each cluster i to the nearest market calculated in Google Earth Engine exploiting the algorithm developed by (Weiss et al., 2018)
- $Fuelcost$ is the local cost of diesel fuel derived with the approach described in (Szabo et al., 2011)
- $lpermin$ is a parameter expressing the average fuel consumption of a truck in litres per minute.

The whole product is multiplied by 2 to simulate a return journey, and by n, which is defined as the ratio of the weight of the total yield gap and the weight that a track journey can transport, thus representing the number of required journeys.

To model groundwater pumping total costs, we refer to the database for recent projects in different countries of sub-Saharan Africa compiled in ref. (Xenarios and Pavelic, 2013), selecting only mechanical electric-powered pumps. In particular, we estimate the following non-linear regression model:

$$TPC_i = h_i \times \beta_1 + y_i \times \beta_2 + h_i \times y_i \times \beta_3 + \varepsilon_i$$

(Eq. A2.13)

where:

- TPC_i are total pump costs, which include both fixed upfront costs (for the installation of the pump) and operational and maintenance costs;
- h_i is the well depth (in m);
- y_i is the pump yield (in l/s).

The model yields a cost function, which is plotted in Figure A2.6 for a $h_i \in (10, 50)$ and $y_i \in (1, 10)$. We then estimate total pumping costs using the model in all clusters of our analysis where groundwater pumping requirements and feasibility criteria are met .

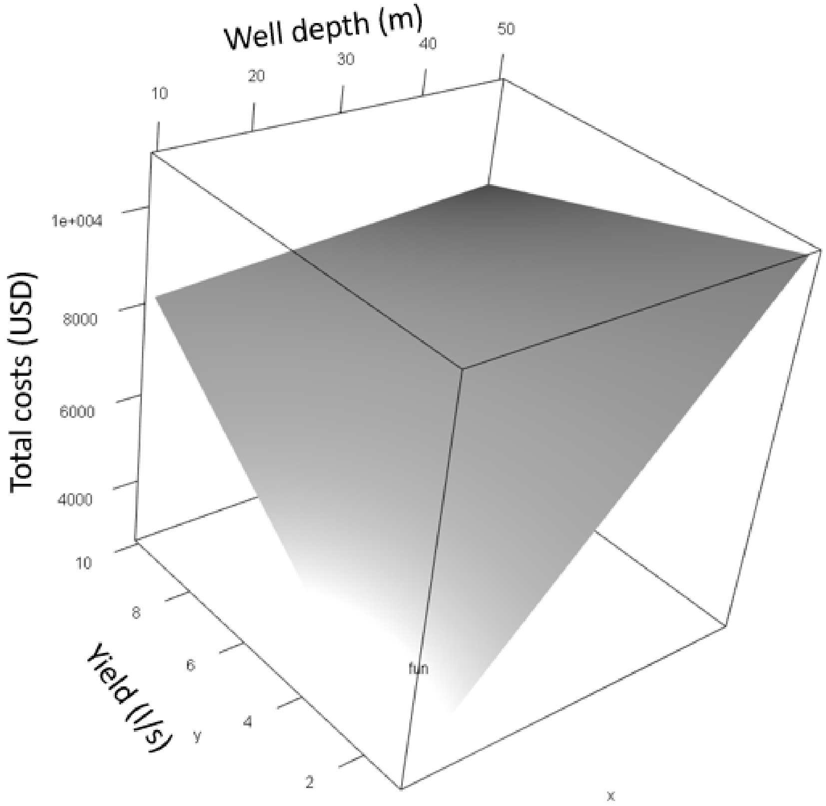


Figure A2.6: 3D surface plot of the non-linear function to assess groundwater pumps total costs

A limitation of our local microeconomic economic analysis is that we do not monetise the intangible benefits of the improved local education and healthcare level as a result of the new electricity input. However, these likely imply both substantial costs savings in terms of human lives and treatment, and a greater accumulation of human capital which in the long-run can yield to significantly larger economic growth, as discussed in the relevant literature (Aguirre, 2017; Daka and Ballet, 2011; Sovacool and Ryan, 2016; Spalding-Fecher, 2005). We encourage studies targeting to quantify those indirect, long-run monetary gains. The same is true for small commercial and productive activities, and the additional value added from local crop processing. We acknowledge that electricity is likely to have a broad array of impacts through complex socio-economic linkages (Riva et al., 2018), including on fertility and migration decisions (Fried and Lagakos, 2017; Grimm et al., 2015).

Supplementary tables

***Table A2.1:** Main data sources in the* M-LED *platform*

Input step	Dataset	Unit	Source (ref. number)	Time resolution	Spatial resolution
Population clustering and residential demand	High Resolution Settlement Layer	Number of people per cell	(Facebook Connectivity Lab and Center for International Earth Science Information Network - CIESIN - Columbia University, 2016)	Annual	30 m
	Wealth distribution, employment levels	Distribution across quintiles; employment rates	(USAID, 2009)	Survey year	Province-level
	GHS-SMOD	Classification urban, rural settlement	(A.J. et al., 2019)	5 years	250 m
	VIIRS DNB nighttime lights	Radiance	(Elvidge et al., 2017)	Monthly (aggregated to annual)	30 arc-seconds
	Electricity access levels	%	(Falchetta et al., 2019)	Annual	450 m

	GADM – global administrative layers	-	(Hijmans et al., 2018)	2018	Country and provincial boundaries
Productive demand	Travel time to nearest feature	hours	(Weiss et al., 2018)	-	1 km
	Cropland extent	Land area (ha)	(Teluguntla et al., 2018)	2015	30 m
	Crop-specific harvested area and yield	Land area (km^2) Yearly yield (tonnes/(km^2)	(You et al., 2014b)	2005	10 km
	Crop processing energy demand	kWh/kg of yield processed	See Table SI3	-	-
	Crop schedule and crop factors	Days and coefficients	See Table SI2; ref. (Allen et al., 1998)	-	-
	Global Agro-Ecological Zone (GAEZ) layers	Area (ha), climate zone	(Fischer et al., 2012)	2005	0.5°
	Groundwater depth, productivity, storage	m, l/s, m	(MacDonald et al., 2012)	2012	5 km
	Surface water basins	Distance (m)	(Pekel et al., 2016)	-	30 m
Services demand	Healthcare facilities	Tier	(Maina et al., 2019)	Existing (2015) and	Exact position

				predicted to 2030	
	Education facilities	Tier	(“Kenya Open Data Initiative - Humanitarian Data Exchange,” n.d.)	Existing (2015) and predicted to 2030	Count of facilities in cluster
Kenya case study	Crop wholesale prices at different markets	USD/ton	(“NAFIS – National Farmers Information Service,” n.d.)	1 year	Exact position

Table A2.2: *Crop schedule and crop factors*

Crop	K_c1	K_c2	K_c3	nd_1	nd_2	nd_3	nd_4	pm_1	pm_2	eta_irr
Maize	0.3	1.2	0.35	30	50	60	40	1503	3010	0.6
Bean	0.15	1.15	0.35	20	30	40	20	1510	0109	0.6
Sorghum	0.3	1	0.55	20	35	45	30	2503	1510	0.6
Sweet potato	0.5	1.15	0.65	15	30	50	30	1503	0109	0.6
Tea	0.95	1	1	90	90	90	90	0101	0101	0.85
Plantain	1	1.2	1.1	120	60	180	5	0101	0101	0.85
Cowpea	0.4	1.15	0.3	20	30	35	15	1503	1510	0.85
Pigeonpea	0.7	1.05	0.95	20	30	35	15	1003	1510	0.85
Vegetables	0.7	1.05	0.95	40	60	50	15	2003	0109	0.85
Arabica coffee	1.05	1.1	1.1	90	90	90	90	0101	0101	0.85
Banana	1	1.2	1.1	120	60	180	5	0101	0101	0.85
Potato	0.5	1.15	0.75	25	30	45	30	1503	0109	0.6
Cotton	0.35	1.2	0.6	30	50	60	55	0101	0101	0.6
Cassava	0.3	1.1	0.5	150	40	110	60	0101	0101	0.85

Pearl millet	0.3	1	0.3	15	25	40	25	1503	1510	0.6
Wheat	0.5	1.15	0.33	15	30	65	40	1503	1507	0.6
Rice	1.05	1.2	0.75	30	30	80	40	0101	0101	0.6
Small millet	0.3	1	0.3	15	25	40	25	1503	1510	0.6
Sugar beet	0.35	1.2	0.7	40	70	75	35	0101	0101	0.6
Sunflower	0.4	1	0.35	25	35	45	25	1503	1510	0.85
Soybean	0.5	1.15	0.5	15	15	40	15	1503	1510	0.6
Groundnut	0.7	1.15	0.6	25	35	45	25	1503	1510	0.6
Rapeseed	0.4	1.1	0.35	25	35	45	25	0101	0101	0.6
Sugarcane	0.4	1.25	0.75	50	70	220	140	0101	0101	0.6

Table A2.3: *Results of the multi-variate random forest regression for residential electricity tiers allocation*

Sample size: 297
Number of trees: 1000
Forest terminal node size: 5
Average no. of terminal nodes: 40.335
No. of variables tried at each split: 3
Total no. of variables: 8
Total no. of responses: 4
User has requested response: acc_pop_share_t1
Resampling used to grow trees: swor
Resample size used to grow trees: 188
Analysis: mRF-R
Family: regr+
Splitting rule: mv.mse *random*
Number of random split points: 10
% variance explained: 46.63
Error rate: 0.03

Supplementary files

F2.1 - Excel File: “Households”:

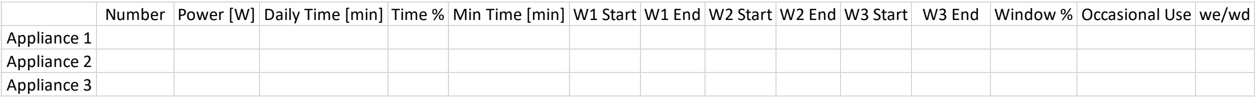
The file is composed of 10 sheets, Rural-1 / Rural-5 accounting for the five modelled tiers of rural households, Urban-1 / Urban-5 for the urban tiers of households of the country.

F2.2 - Excel File: "Services":

The file is composed of 6 sheets, the first one "School" representing the average public primary school of the country and the Hospital-1 / Hospital-5 representing the five modelled tiers of health care units.

The two files are structured in the same way, each of the mentioned sheets, represents the usage pattern of the owned appliances by the described category of user. The sheet is divided into 12 months, for each month appears a matrix accounting for the appliances and the parameters that define their use, in order to account for the seasonal variation of the electric loads. An example is reported in ***Table A2.4.***

Table A2.4: *Parameters describing Appliances Usage Pattern*



	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use	we/wd
Appliance 1														
Appliance 2														
Appliance 3														

All the parameters are described in Table 1 in the manuscript.

F2.3 – PDF file: "Crop processing references"

The PDF file lists the list of studies accessed to define crop-specific processing energy needs.

Supplementary references to Essay 2

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Appendix to Essay 3

Appendix A – Technical ACC electricity requirements estimation

To estimate the technical air conditioning requirement at each location to enable thermal comfort in residential buildings based on the estimated CDDs for each T_{base} value considered, we first size the average basic cooling capacity CC_i^{kW} (i.e. the average household air conditioning unit(s)). Cooling capacity *"indicates the amount of heat the system can remove from the refrigerated space over time"* (Subiantoro et al., 2013). In our study, $CC_i^{kW}$is based on the cooling space volume for rural and urban areas, which in turn is a function of the home volume $CSpace_i$ and the share of the home volume cooled $share\_house\_cooled_i$:

$$CC_i^{kW} = f(CSpace_i, share\_house\_cooled_i)$$

(Eq. A3.1)

As a rule of thumb, on average one cooling ton can cool 45 m^2. In our analysis, we assume that the average urban and rural households require 60 m^2 × 80% = 48 m^2 and 100 m^2 × 35% = 35 m^2 of cooling space, or 120 and 105 m^3 of cooling volume based on assumed room heights of 2.5 and 3 m. The result is expressed in kW (where 1 cooling ton = 3.517 kW).

In our study, we also define the AC-unit energy efficiency ratio (EER) as rural/urban dependent. The EER is defined as the ratio of the air conditioning unit capacity to its power output, i.e. it describes its efficiency:

$$EER = \frac{AC_{capacity}}{AC_{power}}$$

(Eq. A3.2)

The baseline EER is set at 2.2 for rural areas and 2.9 for urban areas based on (Mastrucci et al., 2019). Sensitivity values of 2.2 and 3.2 for urban areas and 2 and 2.9 for rural areas are tested to evaluate the impact of energy efficiency on the results. Based on the cooling capacity and on the local calculated monthly CDDs, we estimate the monthly amount of heat *Q* to be removed from each household in month *m in* joules:

$$Q_{im} = 29 \times n \times \Delta T$$

(Eq. A3.3)

Where 29 is the heat capacity of air at constant pressure in J/mol K; and n is the ratio between $CSpace_i$ in liters and 24, i.e. the molar volume of air at room temperature. ΔT is the differential between the experienced and the desired temperature. This is equivalent to the CDDs in month *m* at location *i*:

$$\Delta T_{im} \equiv CDD_{im}$$

(Eq. A3.4)

We then estimate the monthly hours of peak AC activity (at 100% compressor activity) as the share of the heat capacity to be removed and the cooling capacity of the local AC unit in joules/hour (1 cooling ton = 3.517 kW = 12,661,200 joules/hour):

$$AChours_{im} = Q_{im}/CC_i^{\frac{J}{h}}$$

(Eq. A3.5)

We proceed estimating the additional air conditioning running hours in the average day of month *m* at location *i* (HHD_{im}) when the comfort temperature is reached but needs to be preserved. The factor is set to a base value of 6 hours, which are defined as the hours of cooling requirement in the month *m* with the median CDDs among each month of the year at each location *i.*

Then, we let the factor vary from month to month according to the following rule:

$$HHD_{im} = \frac{CDDs_{im}}{\overline{CDDs_i}} \times 6$$

(Eq. A3.6)

with a cap of 12 maximum cooling hours per day.

To calculate the fraction of the average hour of month *m* in which the compressor is activated by the thermostat to maintain the house at the T_{base}, we first import a monthly solar radiation (W/m^2 on a horizontal surface) raster calculated as the monthly average radiation at each grid cell over the period 1970-2010. Using the *suncalc* R package, we then calculate the sun altitude and azimuth angle at each location for the 15th day of each month of the year, at 1000h (a proxy for the average value over the daytime). We then adjust the horizontal solar radiation SR_{im}^{horiz} to the effective angle as follows:

$$SR_{im} = \frac{SR_{im}^{horiz}}{\tan\left(altitude_{im}\right)} \times \sin\left(azimuth^{wall}{}_{im}\right)$$

(Eq. A3.7)

where tan and sin are the tangent and sine functions, respectively, and $azimuth^{wall}{}_{im}$ is the angle between the orientation of each building wall and the sun azimuth angle.

Then, assuming total window area values of 10 and 15 m^2 in cooled rooms and solar heat gain coefficients of 0.5 and 0.75 for the average urban and rural homes, respectively, we calculate the quantity of energy entering the house windows in the average hour of daytime at each month of the year at each location:

$$\frac{kWh\_im}{h} = \frac{SR_{im} \times windowarea \times k\_solar\_heat\_gain}{1000}$$

(Eq. A3.8)

The share of the average air conditioning hour with operational compressor is then calculated as:

$$share_{im} = \frac{\frac{kWh_{im}}{h} \times 3600000}{CC_i^{\frac{J}{h}}}$$

(Eq. A3.9)

where 3600000 is the conversion factor from kWh to Joules.

Finally, we calculate the power requirement for air conditioning in each month *m* for each household *HH* at location *i* as:

$$ACconsumption_{im}^{HH} = \frac{CC_i^{kW}}{EER_i} \times \ AChours_{im} + \frac{CC_i^{kW}}{EER_i} \times HHD_{im} \times share_{im}$$

(Eq. A3.10)

Namely, assuming that after the base comfort temperature is reached at 100% compressor activity, the compressor then runs $share_{im}$ of the time to maintain the temperature constant net of window heat gain.

Finally, we exploit the gridded distribution of people without electricity access estimated in Section 3.3 and information about average household size in urban and rural areas of each country (United Nations, Department of Economic and Social Affairs, Population Division, 2019) to estimate the total potential electricity demand for air conditioning at each grid cell:

$$ACconsumption_i = \sum_{m=1}^{12} ACconsumption_{im}^{HH} \ \times HHs_i$$

(Eq. A3.11)

Potential CO2 emissions estimation

To complement the analysis, we estimate the potential CO2 emissions that would be generated by ACC use from households currently without access to electricity under the scenarios considered in this paper. In particular, we refer to the statistics about the carbon intensity (kg CO2 / kWh) of the electricity sector of each country from the IEA Energy Balances; for those country lacking information in the database, we assume the baseline national power mixes of 2017 reported from the US EIA International Energy Statistics (EIA, 2017)**.** For those countries, we refer to generalised figures on the direct emission factors for each generation source from (ICF, 2014; Noussan and Neirotti, 2020), reported in Table C.3**.**Global CO2 emissions to meet cooling needs are then calculated as:

$$CO_2^i = \sum_{m=1}^{12} TOTconsumption_i \times \sum sharetech_{ic} \times EF_{ck}$$

(Eq. A3.12)

where i is each grid cell, m identifies months of the year, $TOTconsumption$ is the sum of electricity requirements for AC and fans at each *i*, $sharetech_{ic}$ is the power generation mix of each country c, and EF_{gk} is the CO_2 emission factor of each generation technology k in each country. Note that for households gaining access through decentralised generation solutions we assume an average emission factor of 0.34 kg CO_2 / kWh consumed, based on the technological mix of operational mini-grid projects in sub-Saharan Africa commissioned between 2010 and 2019 (CLUB-ER and CARBON TRUST, 2020). A final necessary remark is that the estimated emissions are not explicitly accounted for in the future climate change scenarios considered in this paper because irrespective of the scenario considered, they remain a marginal share of global CO_2 emissions.

Appendix B – Supplementary Results

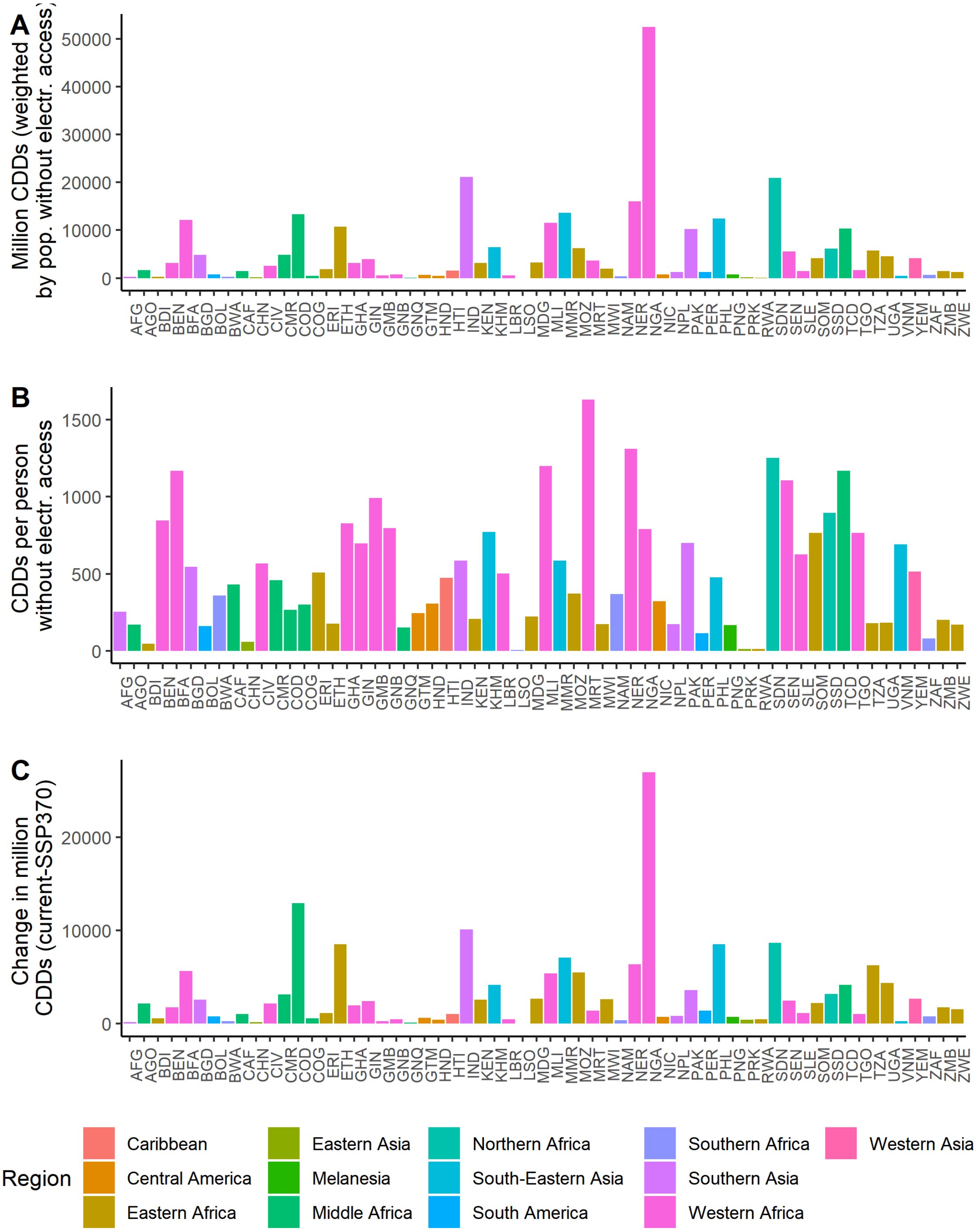


Figure B3.1 | Country-level distribution of unmet CDDs due to electricity access deficit at Tbase=26° C. (A) Absolute number of CDDs per year, million; (B) CDDs per year per person without electricity access, (C) Absolute change in million CDDs per year (historical to SSP370).

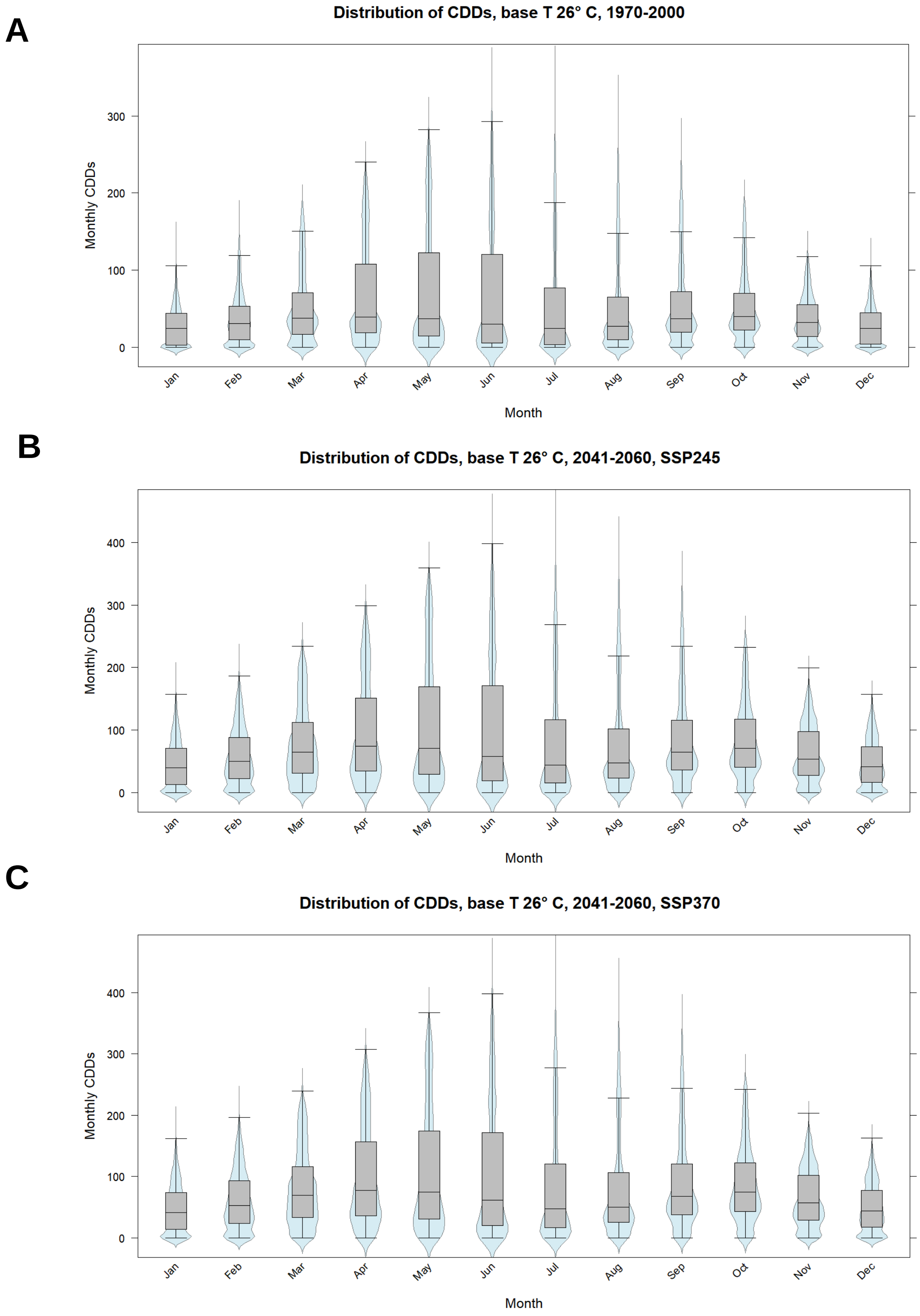
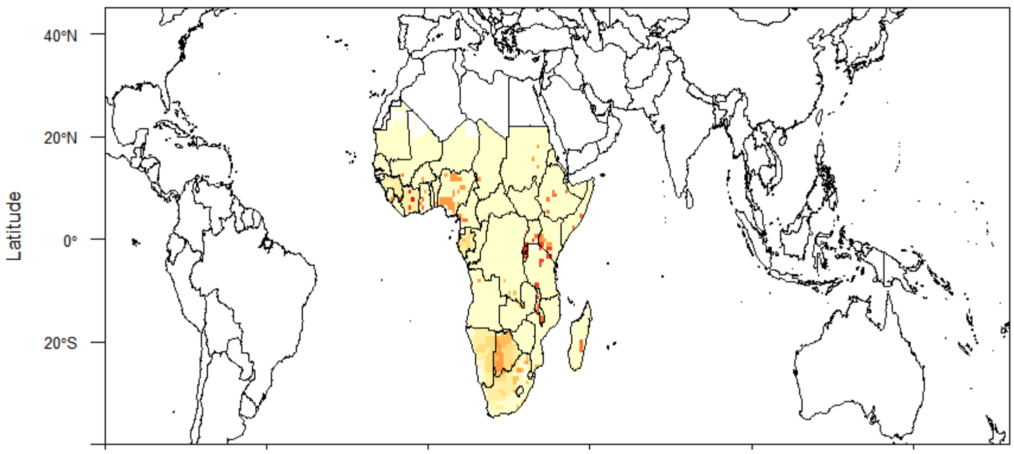
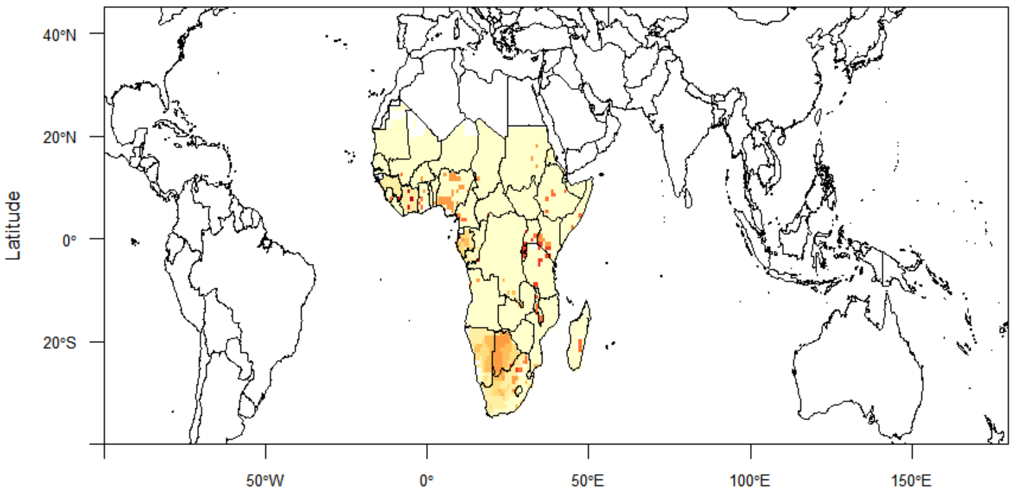


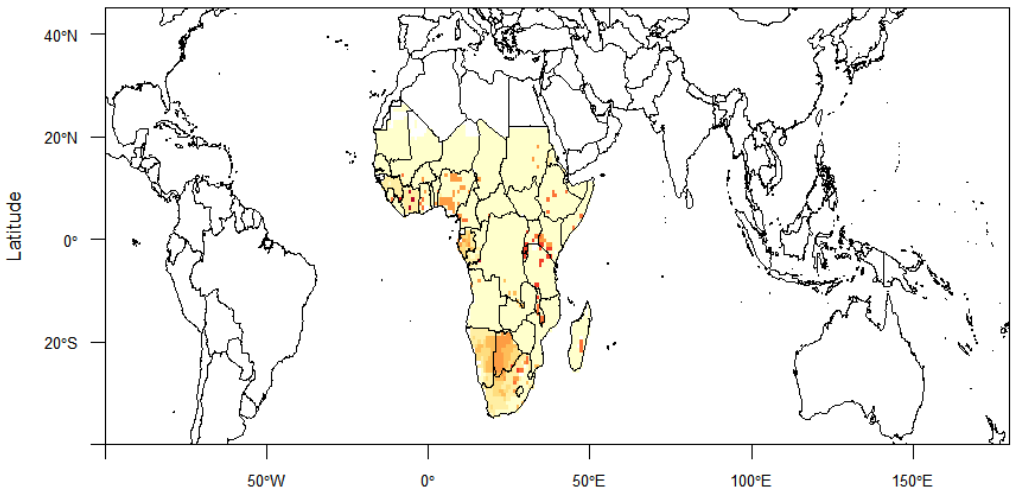
Figure B3.2 | Violin plots of the distribution of monthly CDDs among areas where populations without access to electricity are living in the baseline, SSP246 and SSP370 scenarios. Grey bars show the range of the data; light blue shaded areas show the distribution of the data in that range.



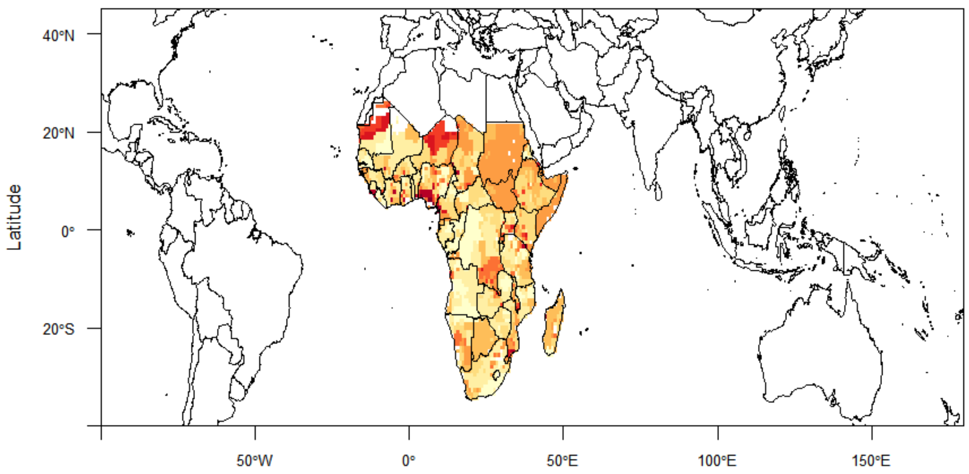
Avg. yearly cooling electricity need / HH, base T 26° C, 2041-2060, baseline, S0



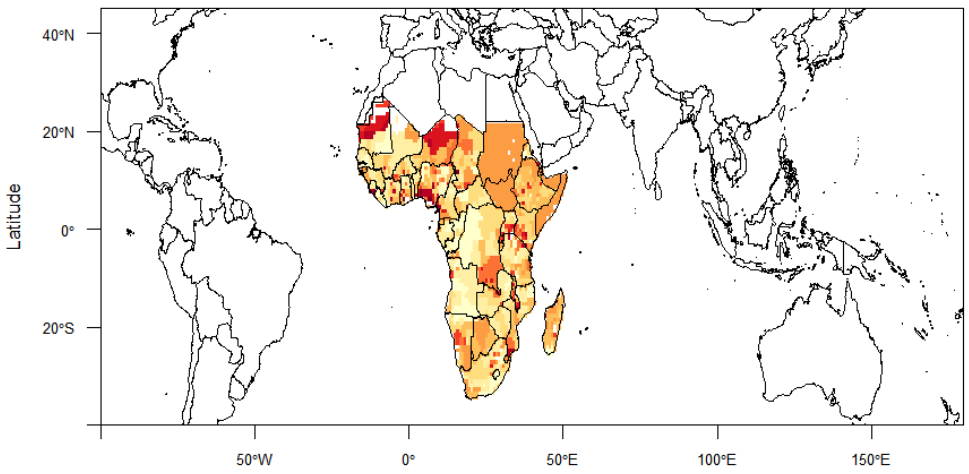
Avg. yearly cooling electricity need / HH, base T 26° C, 2041-2060, SSP245 , S0



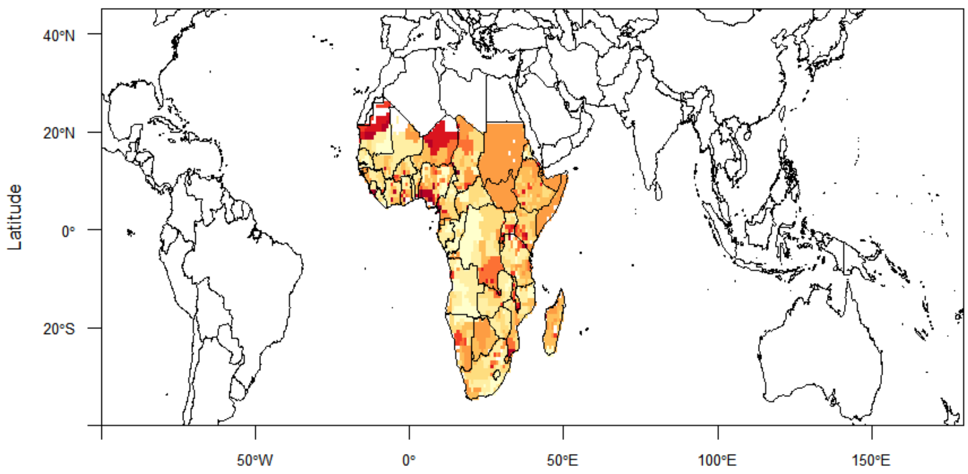
Avg. yearly cooling electricity need / HH, base T 26° C, 2041-2060, SSP370, S0



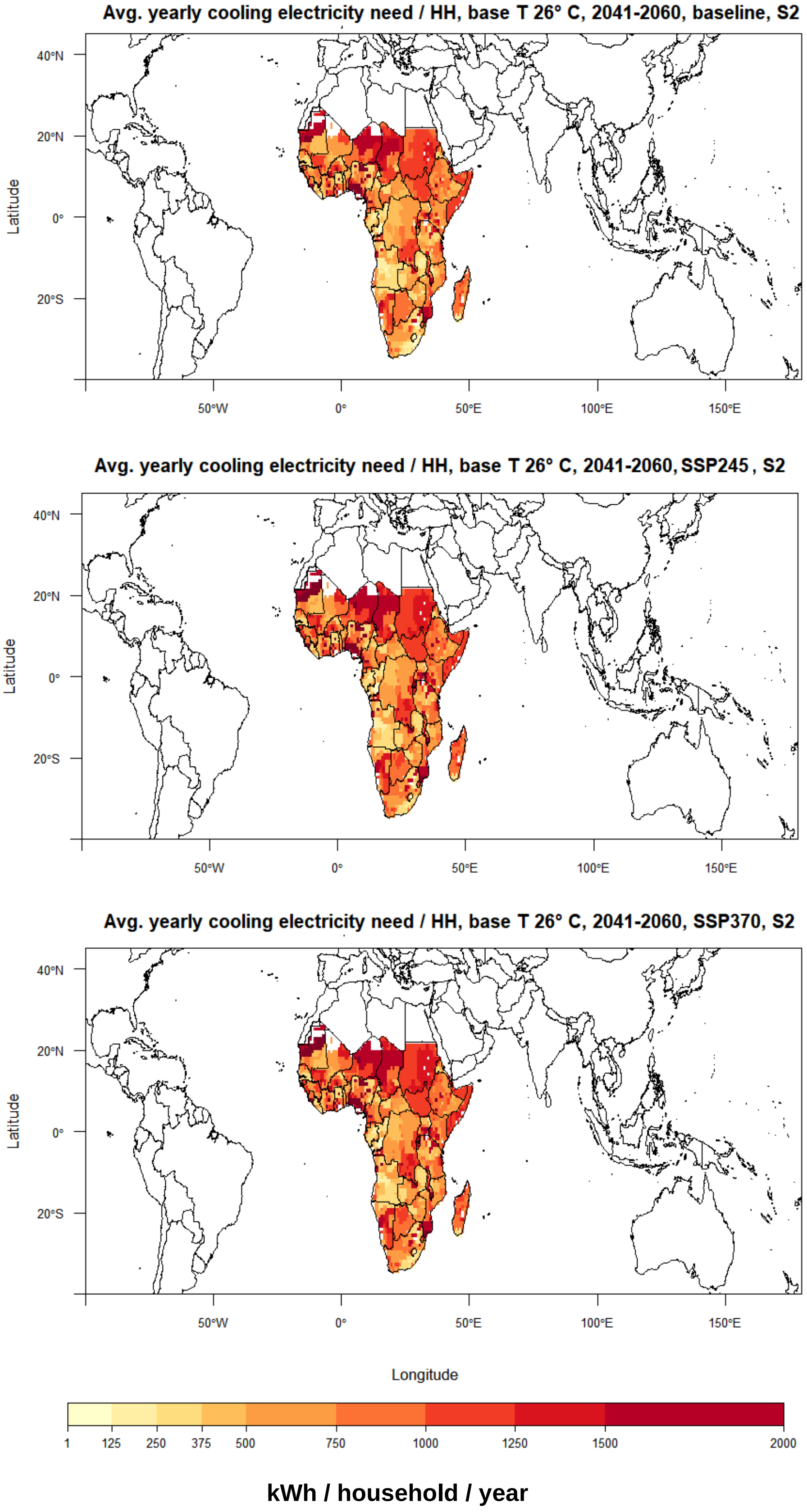
Avg. yearly cooling electricity need / HH, base T 26° C, 2041-2060, baseline, S1



Avg. yearly cooling electricity need / HH, base T 26° C, 2041-2060, SSP245 , S1



Avg. yearly cooling electricity need / HH, base T 26° C, 2041-2060, SSP370, S1



Avg. yearly cooling electricity need / HH, base T 26° C, 2041-2060, baseline, S2

Avg. yearly cooling electricity need / HH, base T 26° C, 2041-2060, SSP245 , S2

Avg. yearly cooling electricity need / HH, base T 26° C, 2041-2060, SSP370, S2

Figure B3.3 | Spatial distribution of electricity consumption (kWh/household/year) for S2 appliance ownership scenarios.

Feedback CO2 emissions from closing the air cooling gap

Based on the estimated electricity requirements, we calculate the CO_2 emissions that would be driven by air conditioning and circulation of households currently without electricity access under the considered scenarios. The results are illustrated in Figure B. 3.4. They closely resemble the trends observed for the latent electricity demand. Under the S2 scenario we estimate a feedback emission potential of 146 Mt CO_2/year, equivalent to about half of the current total emissions from electricity and heat production in sub-Saharan Africa (IEA, 2019).

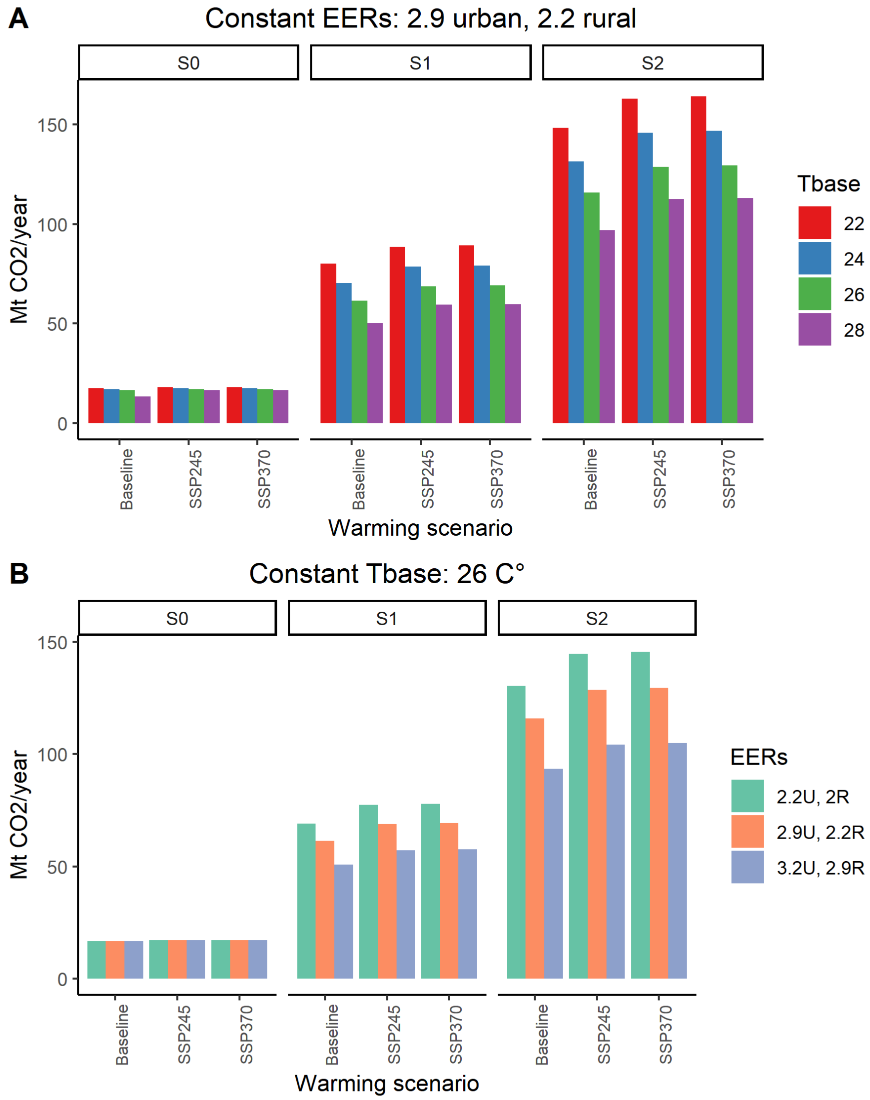


Figure B3.4 | Average yearly feedback CO_2 emissions to meet universal air cooling needs under the assumed parameters for four technology adoption scenarios and three climate scenarios (baseline, SSP245, SSP370). (A) Results under different T_{base} (comfort temperature) targets; (B) Results under different AC-unit EERs (energy efficiency ratios) variants.

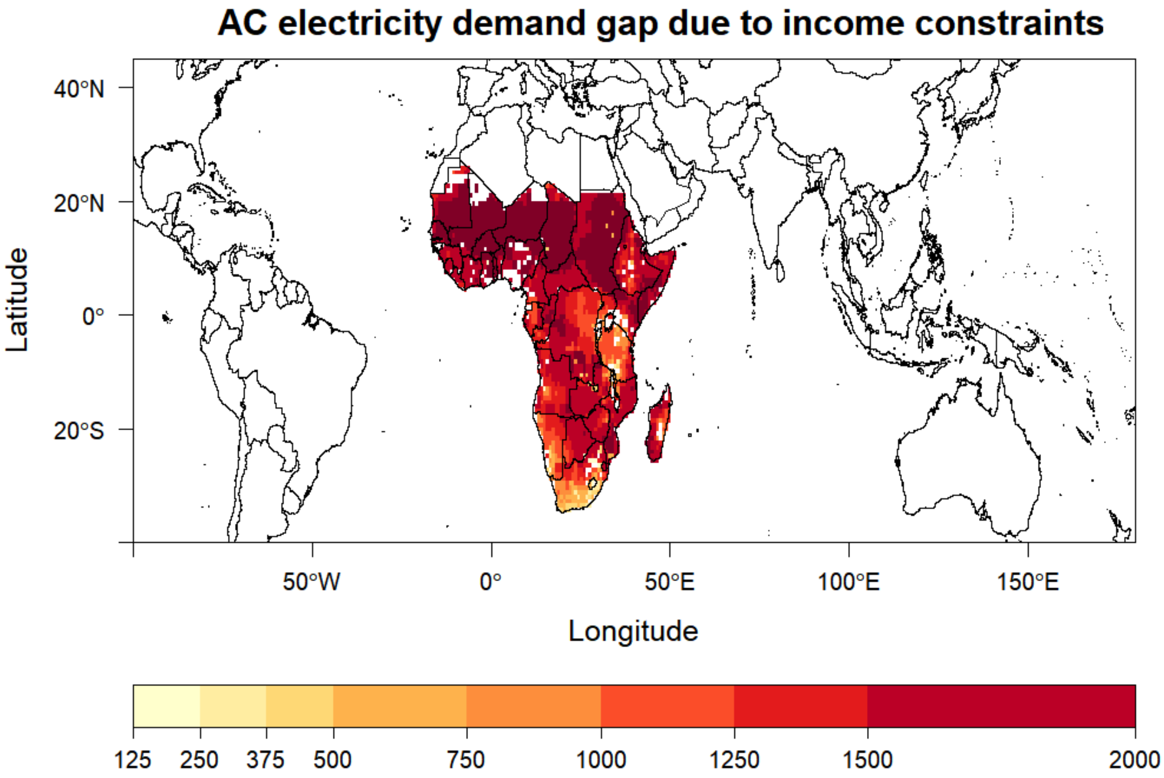


Figure B3.5 | Residual cooling electricity gap map for the S0 scenario under SSP245 due to income constraints (average kWh / household / year).

Appendix C – Supplementary Tables

Table C3.1: Key techno-economic parameters assumed in the electrification model

Category	Parameter	Value
General parameters	Discount rate	17.50%
	Diesel price	1.25 USD / liter
	Population in 2030	1,400,000,000
	Urbanisation level in 2030	50%
Central grid	Central grid connection charge per household	100 USD
	Central grid capacity factor	65%
	Operation and maintenance costs of transmission and distribution lines	2%
	Central grid capacity factor	65%

	Per kWh generation cost for central grid utilities	0.1 USD / kWh
	Central grid distribution losses	20%
	Grid Capacity Investment Cost	2,000 USD / kW
Mini grids	Hydro mini-grid investment cost	4,000 USD / kW
	Wind mini-grid investment cost	4,000 USD / kW
	Solar PV mini-grid investment cost	3,500 USD / kW
	Diesel mini-grid investment cost	900 USD / kW
Standalone solutions	Solar PV standalone investment cost	<50 W: 9000 USD / kW; <100 W: 7500 USD / kW; <1kW: 600 USD / kW; <5 kW: 5000 USD / kW; >5 kW: 4250 USD / kW
	Diesel standalone investment cost	1,200 USD / kW

Table C3.2: Input dataset to the geospatial electrification analysis

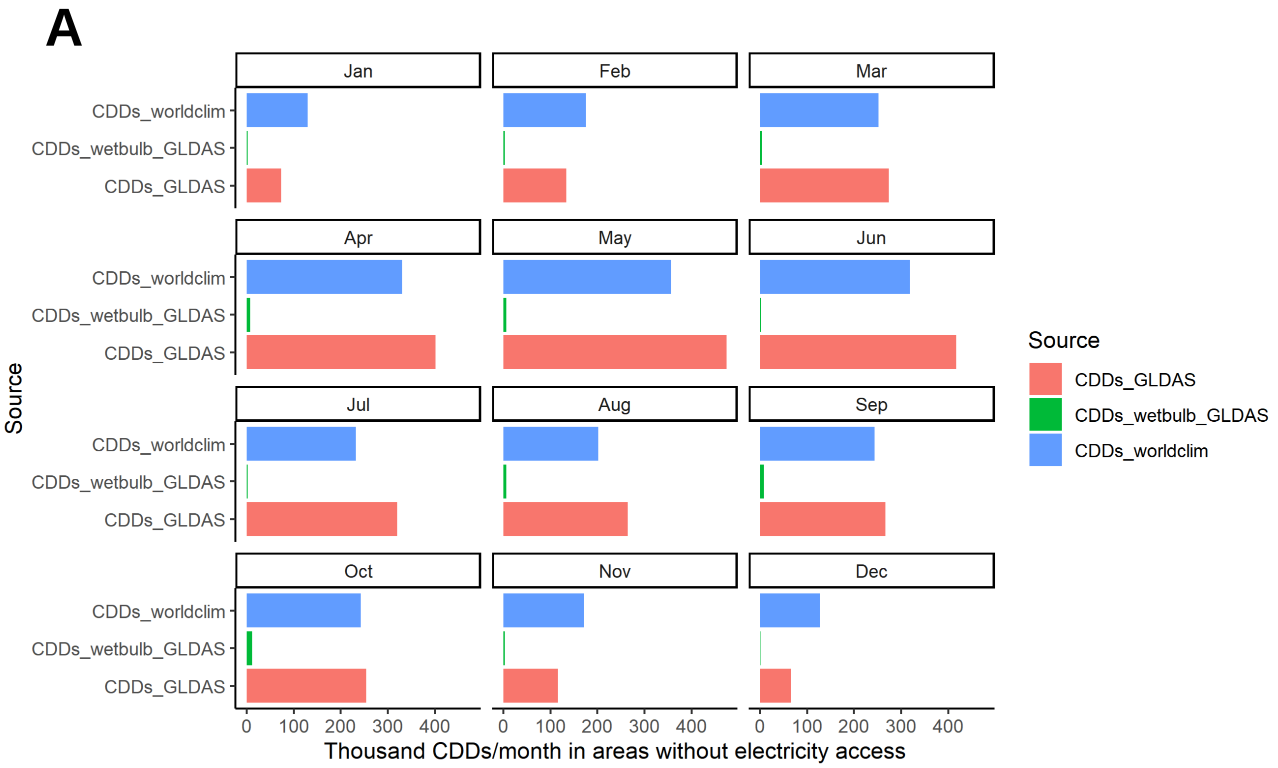
Input dataset	Unit	Source
Elevation	m	(NASA LP DAAC, 2011)
Slope	%	Author's elaboration
Global horizontal irradiation	W/m^2	(SolarGIS, 2017)
Wind speed	m/s	(DTU Technical University of Denmark, 2018)
Administrative boundaries	-	(Hijmans et al., 2018)
Small hydropower potential	MW	(Korkovelos et al., 2017)
Population	Inhabs.	(Tatem, 2017)
Travel time the nearest 50,000+ city	hours	(Weiss et al., 2018)
MV network	kV	(Arderne et al., 2020)
HV transmission network	kV	(Energydata.info, n.d.)
Electricity substations	-	(Energydata.info, n.d.)
Solar restrictions	-	Author's elaboration
Roads	-	(Center for International Earth Science Information Network - CIESIN - Columbia University and Information Technology Outreach Services - ITOS - University of Georgia, 2013)

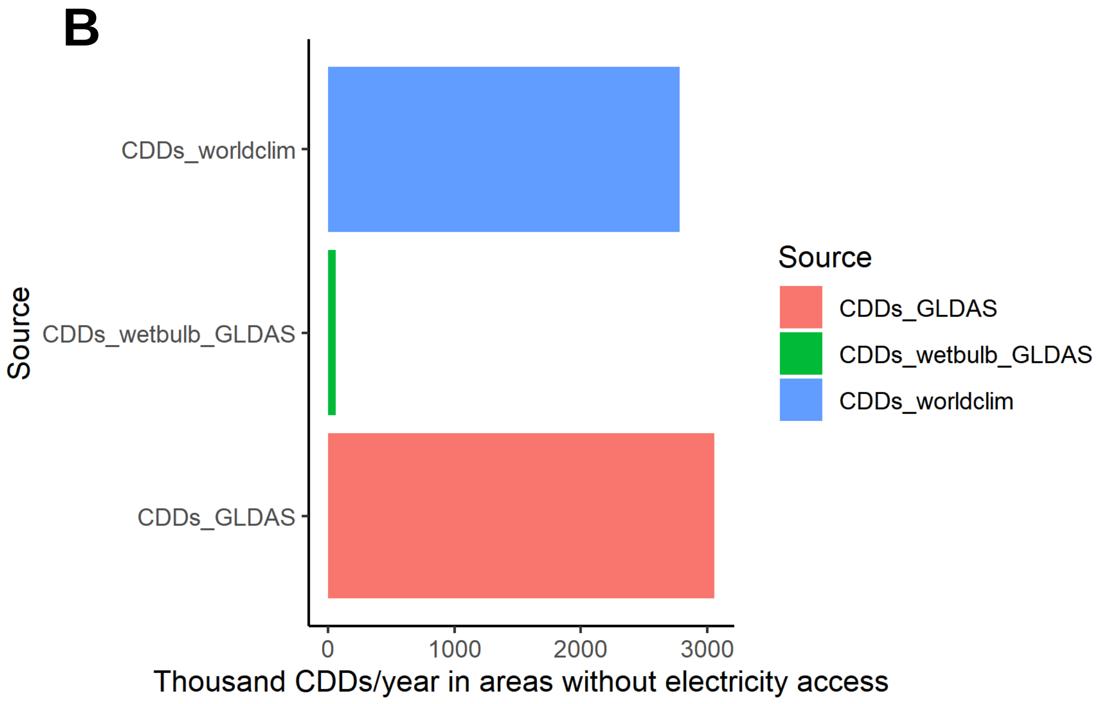
Land cover	Type	(Channan et al., 2014)
Night-time lights intensity	Radiance	(Elvidge et al., 2017)

Table C3.3: Emission factors assumed in the emissions calculation

Technology	**kg CO_2 / kWh**
Oil	0.545
Gas	0.368
RES (solar, wind, hydro, tidal)	0
Waste	0.555
Coal	0.87
Diesel_200kW	0.73
Diesel_2MW	0.587

Appendix D – CDDs primary data source: sensitivity analysis





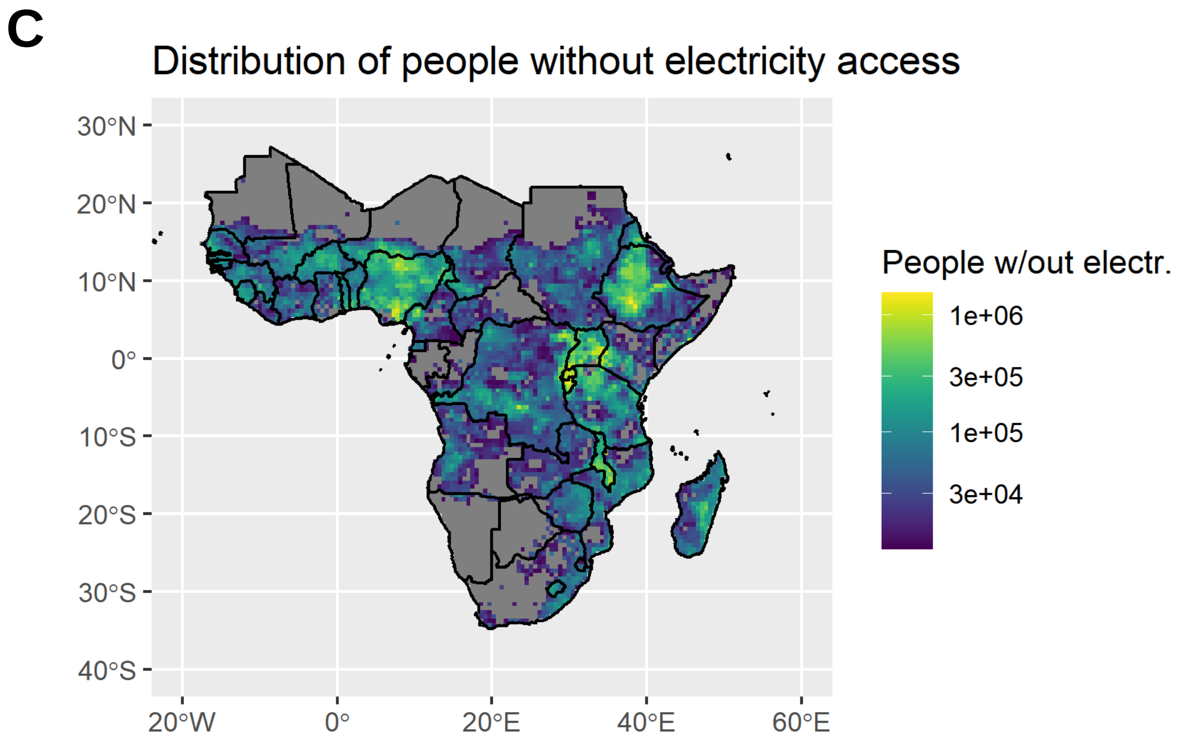


Figure D3.1 | Discrepancy among the different CDD primary data sources considered: (A) monthly CDDs in areas without electricity access; (B) yearly total CDDs in areas without electricity access; (C) Areas without electricity access.

Supplemental References to Essay 3

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Appendix to Essay 4

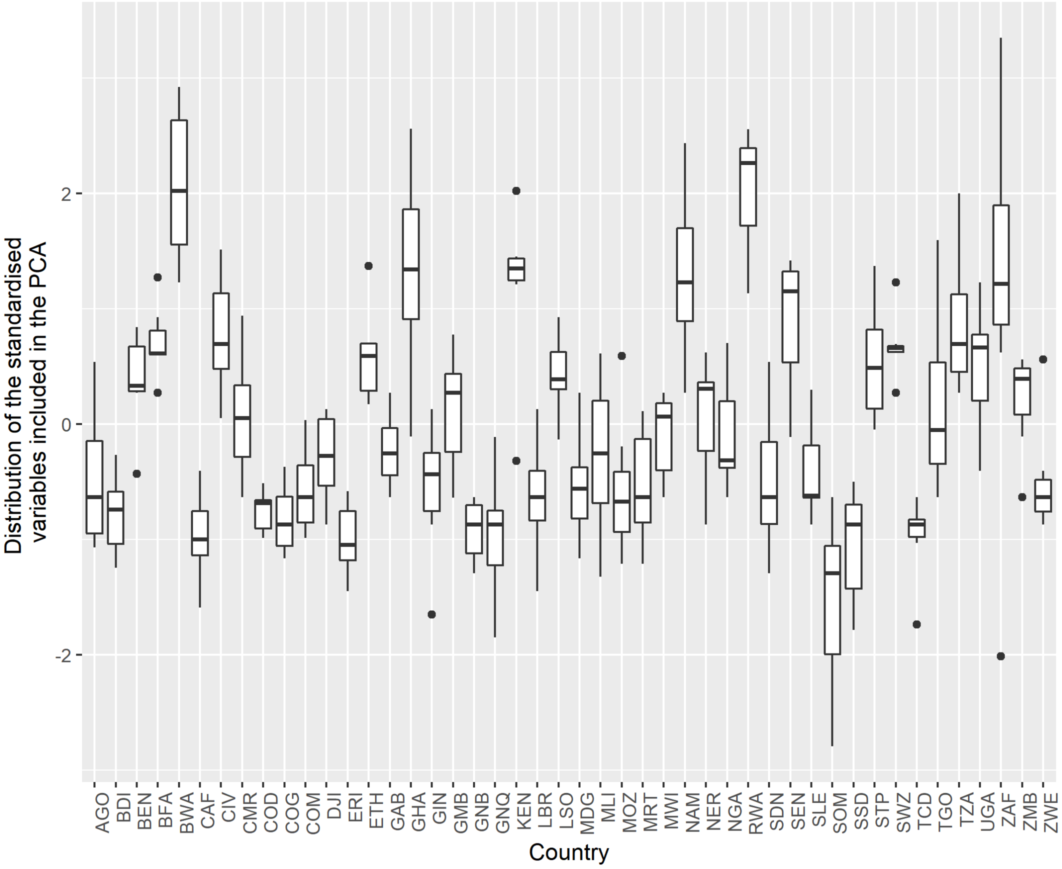


Figure A4.1: *Boxplot of the distribution of the (normalised) variables included in the country-level PCA for the EAGI generation, by country.*

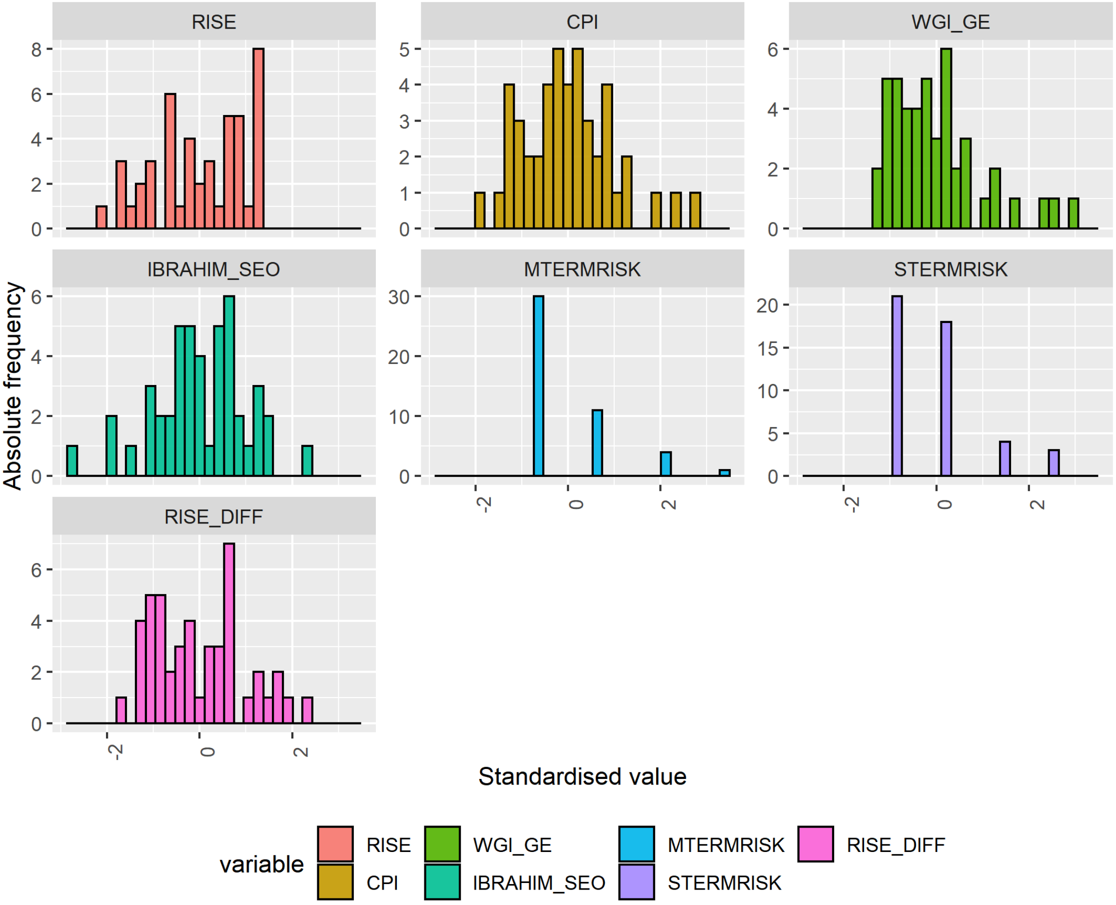


Figure A4.2: *Histograms of the distribution of the (normalised) variables included in the country-level PCA for the EAGI generation, by variable.*

Table A4.1: *Country-specific EAGI*

Country	***EAGI***
Angola	45
Burundi	27
Benin	59
Burkina Faso	68
Botswana	100
Central African Republic	14
Cote d'Ivoire	66
Cameroon	57
Democratic Republic of the Congo	27
Congo	21
Comoros	38
Djibouti	45
Eritrea	19

Ethiopia	70
Gabon	43
Ghana	74
Guinea	39
Gambia	44
Guinea Bissau	24
Equatorial Guinea	31
Kenya	77
Liberia	21
Lesotho	58
Madagascar	23
Mali	32
Mozambique	25
Mauritania	29
Malawi	45
Namibia	91
Niger	56
Nigeria	41
Rwanda	97
Sudan	41
Senegal	60
Sierra Leone	36
Somalia	0
South Sudan	8
Sao Tome and Principe	66
Swaziland	72
Chad	12
Togo	60
Tanzania	76
Uganda	67
South Africa	78
Zambia	59
Zimbabwe	45

EAGI-adjusted discount rate: calculation and results

Table A4.2: *Per-capita regional GDP_PPP in urban and rural settlements in 2030*

Region	URB_Q1	URB_Q2	URB_Q3	URB_Q4	URB_Q5	RUR_Q1	RUR_Q2	RUR_Q3	RUR_Q4	RUR_Q5
Western & central Africa	820	1587	2451	3805	8399	425	787	1179	1773	3674
Eastern Africa	550	1125	1808	2923	7004	427	751	1085	1573	3036
Southern Africa	2049	4605	7916	13710	37937	1004	2160	3599	6037	15611
Republic of South Africa	1228	1995	2732	3751	6522	656	1062	1451	1987	3441

Table A4.3: *Boundary regional consumer discount rates*

Region	***Area***	***Upper bound***	***Lower bound***
Western Africa	*Urban*	*70.4%*	*41.5%*
Eastern Africa	*Urban*	*79.7%*	*44%*
Southern Africa	*Urban*	*61%*	*42%*
Republic of South Africa	*Urban*	*62%*	*18%*
Western Africa	*Rural*	*78%*	*55%*
Eastern Africa	*Rural*	*81%*	*57%*
Southern Africa	*Rural*	*68%*	*51%*
Republic of South Africa	*Rural*	*71%*	*31%*

Detailed EAGI-adjusted discount rate results

Table A4.4: *Country-specific EAGI-adjusted discount rates*

Country	**Rural EAGI-adjusted DR**	**Urban EAGI-adjusted DR**
Angola	58.9%	52.2%
Burundi	67.8%	63.4%
Benin	51.7%	43.4%
Burkina Faso	47.5%	38.1%
Botswana	31.3%	18.1%
Central African Republic	74.0%	71.0%
Cote d'Ivoire	48.3%	39.2%
Cameroon	52.4%	44.3%
Democratic Republic of the Congo	67.8%	63.3%
Congo	70.7%	66.9%
Comoros	62.1%	56.2%
Djibouti	58.7%	52.0%
Eritrea	71.5%	68.0%
Ethiopia	46.3%	36.7%
Gabon	59.5%	53.0%
Ghana	44.3%	34.2%
Guinea	61.7%	55.8%
Gambia	59.1%	52.5%
Guinea Bissau	69.0%	64.8%
Equatorial Guinea	65.5%	60.5%
Kenya	42.9%	32.4%
Liberia	70.3%	66.5%
Lesotho	52.1%	43.9%
Madagascar	69.4%	65.4%

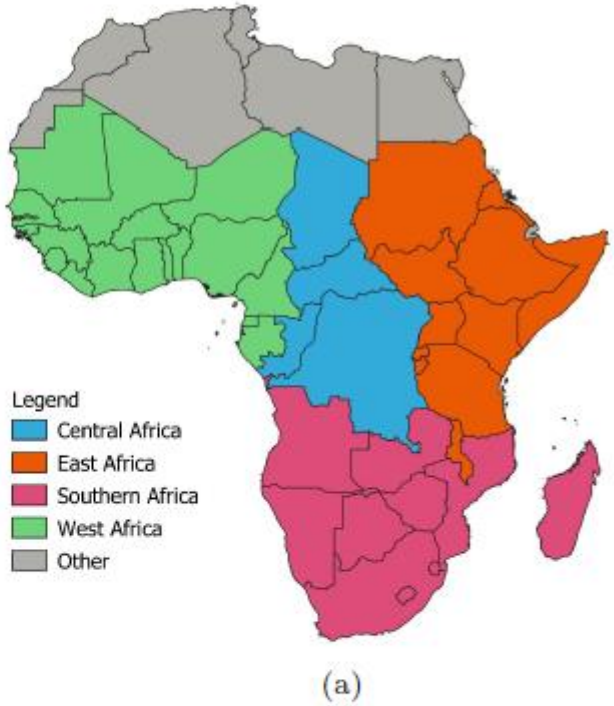
Mali	65.3%	60.2%
Mozambique	68.7%	64.4%
Mauritania	66.7%	62.0%
Malawi	58.8%	52.1%
Namibia	35.5%	23.3%
Niger	53.1%	45.1%
Nigeria	60.5%	54.2%
Rwanda	32.7%	19.8%
Sudan	60.5%	54.2%
Senegal	51.1%	42.6%
Sierra Leone	63.2%	57.6%
Somalia	81.0%	79.7%
South Sudan	77.2%	75.0%
Sao Tome and Principe	48.4%	39.2%
Swaziland	45.0%	35.1%
Chad	74.9%	72.1%
Togo	51.2%	42.7%
Tanzania	43.2%	32.9%
Uganda	47.7%	38.4%
South Africa	42.3%	31.7%
Zambia	51.7%	43.4%
Zimbabwe	58.6%	51.9%

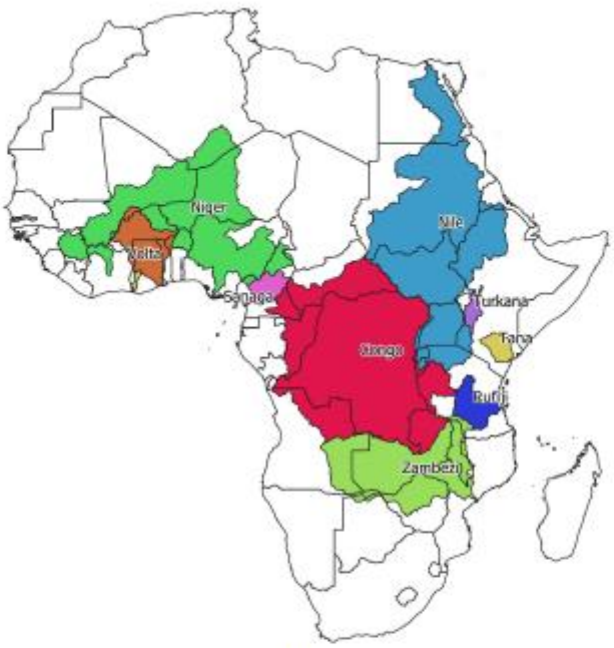
Appendix to Essay 5

Table A5.1: *SPEI index classification*

SPEI values	Drought/flood category
≥ 0.5	Wet
-0.49 -0.49	Near normal
-0.99 - -0.50	Mild drought
-1.49 - -1	Moderate drought
-1.99 - -1.50	Severe drought
≤ -2	Extreme drought

Figure A5.1: *Classification of the regional country groups considered; (b) Location and extent of the nine river basins assessed.*





(b)

Table A5.2: *Reviewed literature about the projected impacts of climate change on hydropower in SSA.*

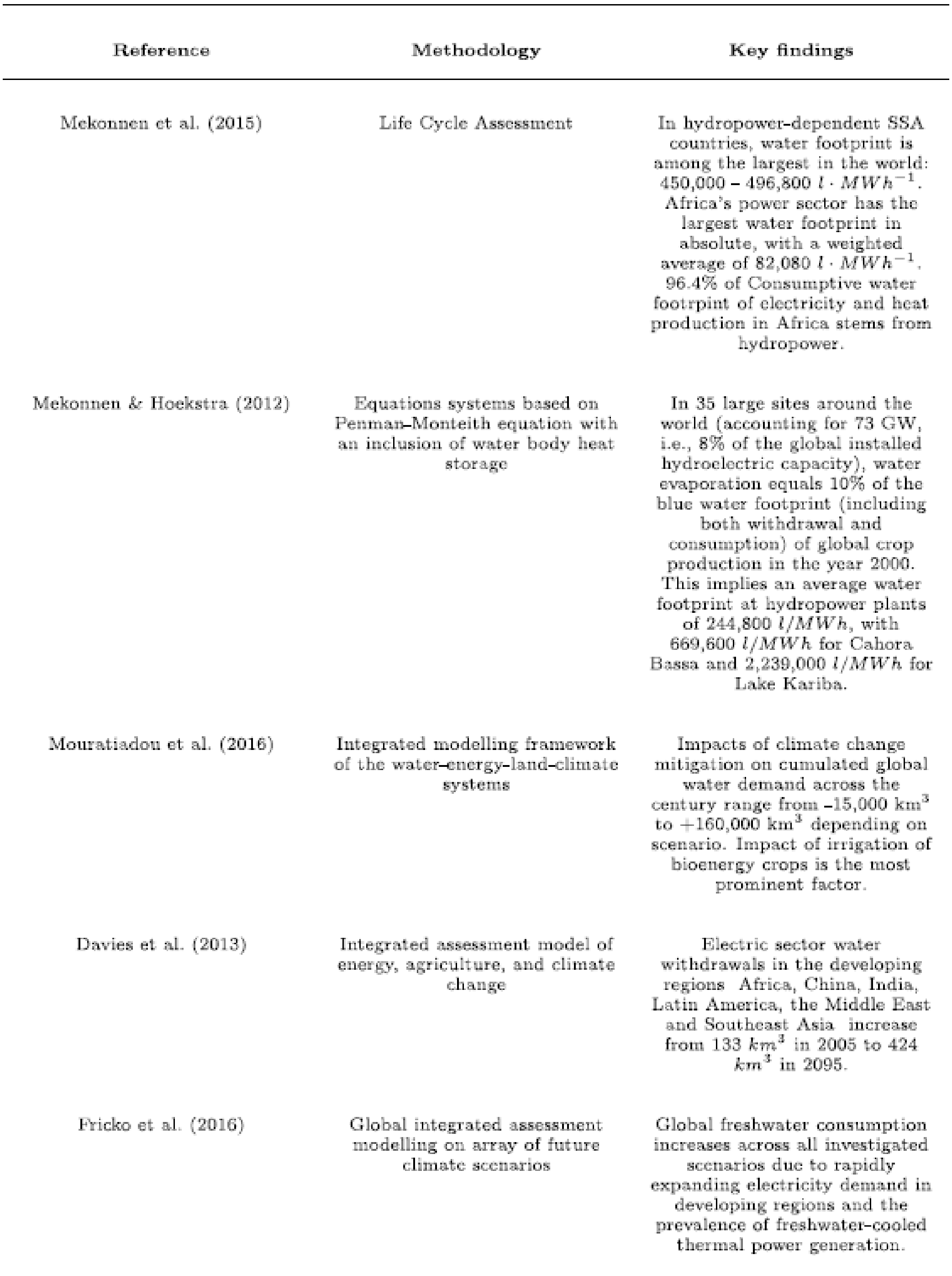
Reference	**Geographical scope**	**Methodology**	**Climate scenarios considered**	**Key findings**
Hamududu & Killingtveit (2012)	Global	Ensemble of simulations of regional patterns of changes in runoff	SRES A1B	+1% hydropower output (globally), regional disparities in SSA (increases in East Africa, decreases elsewhere)
Turner et al. (2017b)	Global	Coupled global hydrological and dam model + IAM	RCPs 4.5 -8.5	0.07-0.13 EJ increase in hydropower output in EA, decreases in SA (0.01 EJ) and WA (0.03 EJ)
Turner et al. (2017a)	Global	Coupled global hydrological + detailed dam model + IAM	SRES A2 - B1	Uncertainty in the direction of change in globally aggregated hydropower production (∼5 to +5% change in mean global production by the 2080s). Negative change in West Africa, positive in East/Horn of Africa and South Africa
Van Vliet et al. (2016a)	Global	Global hydrological-electricity model	Past evidence assessment	Hydropower utilisation rates up to -6.6% and thermoelectric up to -9% during harsh drought years compared to the long-term average for 1981-2010
Van Vliet et al. (2016c)	Global	Three global hydrological models	RCPs 2.6 and 8.5	Global hydropower generation: +2.4-6.3% by 2080 with respect to the 1971-2000 average; in SSA +20% in Central Africa, -20% in parts of Southern Africa

Van Vliet et al. (2016b)	Global	Coupled hydrological-electricity modelling framework	RCPs 2.6 and 8.5	Reductions in usable capacity for 61-74% of the hydropower plants and 81–86% of the thermoelectric power plants worldwide for 2040–2069. In Africa –0.9% in hydropower output and -5.2-17.8% in thermoelectric output by 2050 for both RCP 2.6 and 8.5 if no adaptation is performed.
Conway et al. (2017)	EA and SA	Cluster analysis	–	Hydropower to become increasingly concentrated in the Nile (from 62% to 82% of total regional capacity) and Zambezi (from 73% to 85%) basins.
Cervigni et al. (2015)	Africa	WEAP and OSeMOSYS models	6 representative climate futures (based on A2, A1B, RCP 4.5, RCP 8.5)	In both dry and wet scenarios forgone revenues (5-60% and 15-130%) with no adaptation
Stanzel et al. (2018)	West Africa	Water balance model with regional climate model simulations input data in	RCP4.5 and RCP8.5	Basin heterogeneity. Relative change in rivers' discharge in the range of ±5%. Stronger decreases in the north and east of West Africa and pronounced increases mainly for the southwest.
Kling et al. (2015)	Zambezi river basin	Econometric analysis based on hydrological model outputs	RCP4.5	Basin average annual discharge could decrease by 20% by 2050 and by a range between 40-55% by 2100.
Kling et al. (2014)	Zambezi river basin	Rainfall-runoff model linked to a reservoir model for the Zambezi basin	SRES A2	Future irrigation development imply decreases in line with those currently caused by reservoir evaporation. Discharge highly sensitive to small precipitation changes, but uncertainty over future precipitations.

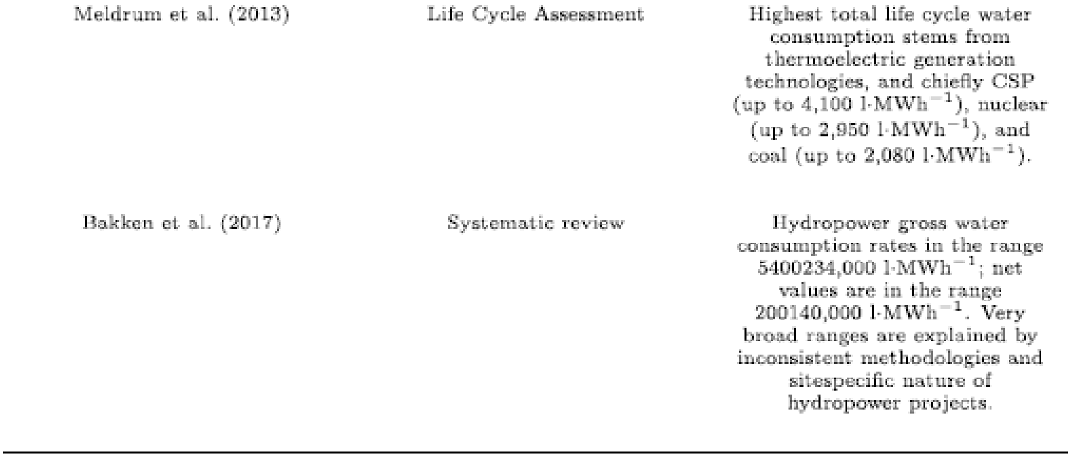
Harrison & Whittington (2002)	Planned Batoka Gorge scheme on the Zambezi River	Coupled water balance, reservoir, electricity market and financial model	HadCM2, HadCM2-S, ECHAM4	Up to 19% of target production unmet, up to \$3.8 million/month of forgone revenues and up to +\$0.40 in unit cost of electricity
Karekezi et al. (2012)	East and Horn of Africa	Qualitative / previous evidence-based assessment	–	Lower water levels at Lake Victoria during 2004-2006 led to decline in GDP growth rate from 6.2% to 4.9%; for 1999-2002 drought in Tanzania, hydropower reduced by 25%, 1-1.5% of GDP lost; in Kenya 1.45% of GDP lost. Emergency capacity costs at 1-3.3% of GDP.
Spalding-Fecher et al. (2016)	Zambezi River Basin	WEAP scenario modelling system	SRES A2 with development of climate envelopes of wetting and drying future	Lake Kariba: potential –12% average electricity generation (20502070)
Kizza et al. (2010)	Riparian Countries of Lake Victoria Basin	Soil Water Assessment Tool	13 scenarios (3°C, 10-30% precipitation)	Site specific
Oyerinde et al. (2016)	Kainji dam in the Niger Basin	Hydroelectricity production model	CMIP5 scenarios	Increases in river flow for the majority of scenarios as a result of increases in precipitation in the headwaters of the basin around 2050; slightly decreasing trends for low emission scenarios.
Uamusse et al. (2017)	Mozambique	Regression analysis on 13 GCMs outputs	SRES B2, A1B, A2	Temperature increased by 0.88°C in last 20 years (expecially during rainy season), potentially up to +3.6°C in 2100 and hydropower capacity reduction in all HPP (current and planned)

Beilfuss (2012)	Zambezi River Basin	Literature review based on GCMs and downscaled regional models results	Range of climate scenarios from IPCC 3rd assessment report	26-40% decline in average annual runoff by 2050 (w.r.t. 1960–90). -32% in reliable hydropower capcity (from 30,000 to 20,000 GWh/year) and –21% in average energy production (from 56,000 to 44,000 GWh/year).
Boadi & Owusu (2017)	Ghana/Volta River Basin	Regression analysis	Past data to determine attribution	Rainfall variability accounted for 21% of inter–annual fluctuations in power generation from Akosombo dam (1970–1990); ENSO and lake water level for 72.4% of fluctuations (1991-2010).
Kabo–Bah et al. (2016)	Ghana	Mann–Kendall test statistic to assess localised changes.	Past data to determine attribution	Upward trend for the discharge of the Akosombo reservoir and a downward trend for the water level (1960–2011)
Sridharan et al. (2019)	Eastern African power pool countries	Energy system model coupled with water systems management model of the Nile River Basin	RCPs	Additional adaptation investments of $4.2 billion required by 2050 to attain fuel and operational cost savings of up to $22.6 billion.

Table A5.3: *Reviewed literature about the impact of power generation on water availability.*



Reference	Methodology	Key findings
Mekonnen et al. (2015)	Life Cycle Assessment	In hydropower-dependent SSA countries, water footprint is among the largest in the world: 450,000 – 496,800 $l \cdot MWh^{-1}$. Africa's power sector has the largest water footprint in absolute, with a weighted average of 82,080 $l \cdot MWh^{-1}$. 96.4% of Consumptive water footrpint of electricity and heat production in Africa stems from hydropower.
Mekonnen & Hoekstra (2012)	Equations systems based on Penman-Monteith equation with an inclusion of water body heat storage	In 35 large sites around the world (accounting for 73 GW, i.e., 8% of the global installed hydroelectric capacity), water evaporation equals 10% of the blue water footprint (including both withdrawal and consumption) of global crop production in the year 2000. This implies an average water footprint at hydropower plants of 244,800 l/MWh, with 669,600 l/MWh for Cahora Bassa and 2,239,000 l/MWh for Lake Kariba.
Mouratiadou et al. (2016)	Integrated modelling framework of the water-energy-land-climate systems	Impacts of climate change mitigation on cumulated global water demand across the century range from –15,000 km^3 to +160,000 km^3 depending on scenario. Impact of irrigation of bioenergy crops is the most prominent factor.
Davies et al. (2013)	Integrated assessment model of energy, agriculture, and climate change	Electric sector water withdrawals in the developing regions Africa, China, India, Latin America, the Middle East and Southeast Asia increase from 133 km^3 in 2005 to 424 km^3 in 2095.
Fricko et al. (2016)	Global integrated assessment modelling on array of future climate scenarios	Global freshwater consumption increases across all investigated scenarios due to rapidly expanding electricity demand in developing regions and the prevalence of freshwater-cooled thermal power generation.



Meldrum et al. (2013)	Life Cycle Assessment	Highest total life cycle water consumption stems from thermoelectric generation technologies, and chiefly CSP (up to 4,100 $\text{l}\cdot\text{MWh}^{-1}$), nuclear (up to 2,950 $\text{l}\cdot\text{MWh}^{-1}$), and coal (up to 2,080 $\text{l}\cdot\text{MWh}^{-1}$).
Bakken et al. (2017)	Systematic review	Hydropower gross water consumption rates in the range 5400234,000 $\text{l}\cdot\text{MWh}^{-1}$; net values are in the range 200140,000 $\text{l}\cdot\text{MWh}^{-1}$. Very broad ranges are explained by inconsistent methodologies and sitespecific nature of hydropower projects.

Supplementary References to Essay 5

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