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Trade-offs and synergies between universal electricity access and climate change mitigation in Sub-Saharan Africa

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ABSTRACT

Access to electricity services is fundamental to development, as it enables improvements to the quality of human life. At the same time, increasing electricity access can have notable consequences for global climate change. This paper analyses trade-offs and synergies between achieving universal electricity access and climate change mitigation in Sub-Saharan Africa, using the IMAGE-TIMER integrated assessment model. For this purpose, we analysed developments in a number of indicators that describe demand, production, and costs of the future power system under various scenarios with and without climate change mitigation policies. The results show that, achieving universal electricity access requires an annual investment of USD 27–33 billion until 2030 on top of baseline investment. There is a strong synergy in emissions reduction and investment savings, particularly driven by the regions' efficiency improvements of household appliances (the purchase of efficient appliances and the efficient use of the appliances). On the other hand, climate mitigation policies are projected to increase the cost of electricity per kWh, depending on fossil fuel share in the mix. Therefore, we conclude that, climate policies will need to be combined with complementary policies- e.g. pro-poor tariffs, fuel subsidies, and cross subsidization- to protect the poor from increasing electricity prices.

1. Introduction

Ensuring access to affordable, reliable, sustainable and modern energy for all is one of the Sustainable Development Goals (SDG7) (Un, 2015) and is also acknowledged by the Paris Agreement as an important need (Unfccc, 2015). The key rational behind the emphasis on energy access is that access to modern energy services is fundamental to development (Hollberg, 2015). Access to electricity, for instance, allows the use of appliances like mobile phones, radios and fans, while lighting provides extra hours to study or work. Still, over 1.2 billion people did not have access to electricity in 2013; more than half of which live in Sub-Saharan Africa (IEA, 2014). Achieving SDG7 thus requires Sub-Saharan African countries to expand electricity access substantially, especially since population is projected to grow rapidly. However, the goal of increasing electricity access is coupled to other SDGs and societal goals, including mitigation of climate change (Van Vuuren et al., 2012). This is also explicitly recognized by SDG7, which, next to universal access to modern energy sources, also includes targets on renewable energy and energy efficiency.

There are a number of possible trade-offs between providing access to electricity and climate policy. One such trade-off is that increasing electricity access could contribute to greenhouse gas emissions, both directly by increasing energy consumption, and indirectly by promoting economic growth (IRENA, 2015). Several studies have shown that the direct impact of providing electricity access is relatively small: These studies typically find an increase in emissions of around 2–4% (See for instance Van Vuuren et al., 2012 and Un-Ohrlls, 2014 for studies at the global scale, Pachauri, 2014 for India, and Sanchez and Tozicka, 2013 on South Africa). The reason is that additional energy consumed by poor households is expected to be very small compared to the average consumption, while the newly gained access contributes significantly to human development. The indirect impact from promotion of economic growth is more uncertain and more difficult to assess, and will most likely be a long-term effect. Another possible trade-off is that policies aimed at climate change mitigation can negatively impact energy access by increasing energy prices. For instance, several studies have shown that mitigation policies could slow down the switch from traditional biomass to modern fuels for cooking and heating (Cameron et al., 2016; Daioglou et al., 2012; Lucas et al., 2013).

To the best of our knowledge, there are no studies in literature that specifically explore the relationships between climate mitigation policies and electricity access in Sub-Saharan Africa. This study addresses

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these omissions by analysing the impact of mitigation policies on electricity access in Sub-Saharan Africa, as well as the impact that achieving universal electricity access in Sub-Saharan Africa has on global climate change. Furthermore, most existing studies on electricity access in Sub-Saharan Africa (Deichmann et al., 2010; Bazilian et al., 2012; OECD/IEA, 2015) assume a fixed minimum level of electricity consumption for all households, neglecting the dynamic process where electricity consumption increases with growing wealth. In this study, we assess the impact of different electricity consumption levels for urban and rural households and various income layers. As such, the main research question of this article is:

1.1. What are key synergies and trade-offs between improving electricity access and climate mitigation in Sub-Saharan Africa?

As a continuation of our previous work (Dagnachew et al., 2017), which addresses the effect of various levels of electricity consumption on installed capacity and investment, this paper presents the interaction between universal electricity access and climate change mitigation efforts. We focus on a number of indicators that describe demand, production, and costs of future developments in the power system in Sub-Saharan Africa under several scenarios. The scenarios differ with regard to electricity access targets and implementation of climate mitigation policy. We have used the Integrated Assessment Model (IAM) IMAGE-TIMER (Van Vuuren et al., 2014), including the electrification model described in Dagnachew et al. (2017) and the household electricity demand model described in Daioglou et al. (2012). This model is particularly suited to the analysis, as it combines a detailed electrification model containing several on-grid and off-grid electrification options, with an IAM that takes into account the synergies and trade-offs with (global) climate mitigation policies. The choice between electrification systems (grid, mini-grid and stand-alone) is based on local data about socio-economic characteristics, and potentials and prices of various off-grid technologies (solar PV, wind power, mini-hydro, diesel generators).

The structure of the rest of the paper is as follows: Section 2 presents the methodology employed in this paper, where the model and the scenarios are described; Section 3 presents the results using the indicators listed above; Section 4 presents a brief discussion on the model performance and results and uncertainties, and Section 5 provides conclusions on policy implications and suggestions for further research.

2. Methodology

2.1. The IMAGE-TIMER model

The IMAGE model is an integrated assessment model looking at future global environmental change (Stehfest et al., 2014). It represents interactions between society, the biosphere and the climate system to assess sustainability issues such as climate change, biodiversity loss and human well-being. In this paper, we use the energy-system simulation model (TIMER), a sub-model of the IMAGE framework (Van Vuuren et al., 2006, 2016). We focus on household electrification, using the electrification sub-model described in Dagnachew et al. (2017) and the household electricity demand sub-model described in Daioglou et al. (2012).

TIMER describes the demand and supply of 12 different energy carriers for 26 world regions. In the model, Sub-Saharan Africa is divided into four regions: 'western & central Africa', 'eastern Africa', 'Republic of South Africa', and 'the rest of southern Africa' (see Fig. i in the Supplementary text). Key issues that TIMER addresses are transitions to more sustainable energy supplies; exploitation of energy resources to meet future demand; and the potential role of the energy conversion sector and individual technologies, particularly in power production, in achieving a more sustainable energy system. In choosing energy supply carriers, TIMER uses a multi-logit approach that selects predominantly the cheapest energy technologies, but assigns a market share to technologies that have somewhat higher costs as well, taking into account heterogeneous local characteristics where relevant. In some exceptions, optimization algorithms are used for simplification. In order to represent climate policy in the model, a 'carbon price' is introduced to induce a shift towards low-carbon technologies. Key mitigation options include increasing the share of nuclear power and renewables, equipping fossil-fuel technologies with Carbon Capture and Sequestration (CCS), improving energy efficiency, and reducing non-CO_2 greenhouse gas emissions. More detail on the assumptions and parameters of the TIMER model can be found in Van Vuuren et al. (2006).

Household electricity demand is determined for five income classes, for both rural and urban households, based on the demand for different energy services. The household demand model projects the electricity demand by looking at the specific end-use function (i.e. cooking, appliances, and lighting) and their drivers (population, floor space, appliance ownership, appliance efficiency, weather, and electricity price) and relating these functions to economic development. Empirical data shows that household electricity consumption correlates positively with income, which is used in the model, taking into account appliance ownership (Daioglou et al., 2012). Next to income, total household electricity consumption is determined by appliance efficiency. Change in appliance efficiency is driven by two mechanisms: global autonomous improvement towards a theoretical maximum, and regional improvement stimulated by regional energy prices. Increasing electricity price, for example due to carbon tax, stimulates efficiency improvement, hence, a decrease in household electricity consumption. Subsequently, the investments in different end-use technologies (and fuel types) to fulfil demand depend on their relative costs (although some services like lighting and appliances can only be fulfilled by electricity).

Part of the household demand model is the electrification sub model. This model, discussed in detail in Dagnachew et al. (2017), is integrated within the TIMER model, to allow analysis of trade-offs and synergies between electricity access and climate change mitigation (Fig. 1). The model is designed to assess future developments in household electricity access and the role of different technologies. The model determines the least-cost electrification technology (grid-based, mini-grid or stand-alone) per grid-cell, based on the lifetime cost of generation, transmission and distribution of each technology and the consumption density (kWh per km^2 area) of the respective grid-cell, under various policy assumptions (see Section 2 in the supplementary text). The model also calculates the associated investment requirements. The model operates at a $0.5^\circ \times 0.5^\circ$ grid-cell basis and takes key characteristics of the electricity sector into account. Off-grid electrification technologies include mini-grids based on diesel generators, mini-hydro, solar, wind (the last two potentially in combination with a diesel generator), and stand-alone systems based on solar power or diesel generators. The model uses exogenous data on population density (Bright et al., 2013), distance from existing high-voltage power lines (Open Street Maps, 2015) and endogenous data on resource availability (Hoogwijk, 2004), regional electricity prices, and the costs of individual electrification technologies for central grid, mini grid and stand-alone systems.

2.2. Scenario descriptions

Four scenarios are used in this paper to assess the impact of climate mitigation policy on achieving the universal access target, and vice versa: a baseline scenario (BL), a universal electricity access scenario without climate policy (UA), a universal access scenario with global climate mitigation policy imposed in all regions (UA-CP), and a universal access scenario with global climate mitigation policy where Sub-Saharan Africa is exempted from carbon price (UA-NCP). Table 1 provides a short description of these four scenarios.

The scenarios are all based on the exogenous assumptions and