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To cite this article before publication: Anteneh Getnet Dagnachew *et al* 2020 *Environ. Res. Lett.* in press https://doi.org/10.1088/1748-9326/abcbb9

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Integrating energy access, efficiency and renewable energy policies in Sub-Saharan Africa: a model-based analysis

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Abstract

The role of energy in social and economic development is recognised by sustainable development goal 7 that targets three aspects of energy access: ensure universal access to affordable, reliable and modern energy services, substantially increase the share of renewable energy, and double the global rate of improvement in energy efficiency. With the projected increase in population, income and energy access in Sub-Saharan Africa, demand for energy services is expected to increase. This increase can be met through increasing the supply while at the same time improving households' energy efficiency. In this paper, we explore the interactions between the three SDG7 targets by applying two Integrated Assessment Models, IMAGE and MESSAGE, that incorporate socio-economic heterogeneity of the end-user. The results of the study depict the synergistic relationships between the three SDG7 objectives. Relative to pursuing only the universal access target, integration of all three targets could i) reduce residential final energy consumption by up to 25%, enabling the use of mini-grid and stand-alone systems to provide better energy services, ii) cut annual energy-use-related residential emissions by a third, and iii) lower energy related investments by up to 30% to save scarce finance.

1. Introduction

Ensuring universal access to affordable, reliable, sustainable and modern energy is one of the Sustainable Development Goals (SDG) [1] and is also acknowledged as an important objective by the Paris Agreement [2]. SDG7 covers three aspects of energy access: (1) ensure universal access to affordable, reliable and modern energy services, (2) increase substantially the share of renewable energy in the global energy mix, and (3) double the global rate of improvement in energy efficiency [1]. A growing number of countries have implemented policies to achieve these targets. However, these policies are often not coordinated or coherent, and usually different organizations take the lead on access, efficiency and renewable energy.

Using more efficient appliances helps to provide energy services to more consumers [5-8]. Effective efficiency interventions can also lower generation costs, reduce peak demand, reduce the need for fuel imports, and increase the value of decentralized systems [9, 10]. The growing use of end-use appliances could increase demand and, in particular, peak loads. This can be managed by introducing high-efficiency end-use appliances, allowing energy-service providers to save on investments in new capacity. Similarly, where decentralized generation is in place, energy efficiency enables consumers to derive greater benefit from the electricity supplied. Clear synergies among the targets exist, but just how important these interactions are is as yet uncertain.

While there are several studies investigating the interlinkages between various SDGs [3, 4], the interactions among the three SDG7 targets has hardly been explored, and particularly not for developing regions, such as sub-Saharan Africa (SSA). Despite having a considerable renewable energy potential [11], SSA is a region with the largest energy access deficit globally. This situation is not expected to improve much without new policies [10]. A key question therefore is how to achieve the SDG7 goals in SSA given the interactions among this three targets. The main questions that we aim to answer here is:

"What are the synergies and trade-offs between universal access to clean and modern energy, higher energy efficiency, and increased renewable energy deployment?"

To answer this question, we develop a set of model-based scenarios that quantitatively investigate these interactions. We employ two Integrated Assessment Models (IAMs), IMAGE [12] and MESSAGE [13, 14], with a focus on the residential sector. We distinguish between end-use services related to space heating, space cooling, water heating, cooking, lighting and other household appliance use. Existing international and national energy statistics and balances are still quite aggregate and provide data by fuel source but not by end-use. Determining energy by end-use services therefore requires either scaling-down aggregate national data or scaling-up from detailed household survey data sources. The two models employ these two different approaches to better reflect the uncertainty in end-use energy data.

So far, future scenario assessments have focused on total regional or sectoral energy demands and related emissions. However, simulating residential energy demand in the context of the SDGs requires a detailed study of the end-uses energy supplies and socio-economic heterogeneity in peoples' access to these services. This is critical, particularly in developing countries, for capturing the differences in circumstances and preferences across rich and poor in rural and urban settlements as the challenge is not just mitigating energy-use-related residential emissions, but also addressing access, affordability and local environmental concerns. Both IMAGE and MESSAGE, have the capability to incorporate socio-economic heterogeneity on the end-user's side. We consider differences across settlement patterns (urban and rural) and household incomes.

The paper is organized as follows: we present the methodology in section 2, followed by the results in section 3. Section 4 presents the discussion and section 5 the conclusions.

2. Methodology

The two IAMs we employ here have very distinct model architectures, ways of incorporating socio-economic heterogeneity, and assumptions regarding how demand is determined and availability of supply options. The SI provides detailed descriptions of the model structures, data inputs and assumptions. Both models have been used in numerous scientific publication and further descriptions of the models and their application can be found in [15-20] for IMAGE-TIMER and [21-25] for MESSAGE-Access. Here, we only discuss some of the significant differences in the models that help explain the results that follow.

In IMAGE-TIMER, energy demand is simulated based on changes in population size, GDP and urbanization and demand is closely coupled to the overall IMAGE system-dynamics model. Multinomial logit functions are used to determine fuel and appliance choices for heterogeneous households by distinguishing between rural and urban regions and five income quintiles in each. The model captures competition between various supply technologies to meet required energy demands at least-cost. MESSAGE-Access, on the other hand, uses a simulation based structural approach to estimate household appliances and energy demand within the framework of an indirect utility maximization model. In contrast to IMAGE-TIMER, in MESSAGE-Access appliance choices and energy demands are estimated bottom-up directly employing microdata from national household surveys. Heterogeneity in socio-economic circumstances is captured through simulating the entire population distribution jointly considering variations in household size, income and rural or urban location. We compare and contrast these very different modelling approaches in this work so as to better capture uncertainties arising from differences in model structure and data.

Another major difference between the two models is how useful energy demand for cooking is estimated. IMAGE-TIMER assumes a constant useful energy demand, implying that efficiency improvements will reduce the average per capita demand. This assumption is based on literature, e.g. Ang [37] finds that energy demand for cooking is not income elastic and the level of useful energy consumption per person is fairly constant over time. Similarly, Daioglou, van Ruijven [15] found no statically significant relationship between region, income and useful energy demand for cooking. MESSAGE- Access on the other hand, uses estimates of useful energy demand for cooking directly from microdata. Household survey data from several SSA countries reveal differences in the useful energy demand for cooking by income level and location. Thus, in MESSAGE-Access, cooking energy demand can rise if the rebound effect is stronger than the efficiency gains leading to higher energy consumption per capita.

A third significant difference is in how bullish they are in their assumptions regarding the availability of cleaner stoves and fuels in the future. Given its nature as a data-driven household demand model, as long as households are able to afford fuels and stoves at the given prices, costs and budget constraints, MESSAGE-Access assumes no limitation in supply to households, with the exception of electricity that requires a connection for use. With an increase in income over time, households are therefore able to afford more efficient cookstoves in MESSAGE-Access. In IMAGE-

TIMER, in contrast, the progress towards cleaner cooking solutions are assumed to be limited by historic relationships between access and GDP.

Fourth, MESSAGE-Access considers investments requirements in energy production, and appliance and stove acquisition only, and, unlike IMAGE-TIMER, excludes investments in electricity transmission and distribution.

2.1. Scenario descriptions

The baseline scenario is based on the SSP2 projection of the Shared Socioeconomic Pathways (SSP). The SSPs describe the future evolution of key aspects of society that together imply a range of challenges for mitigating and adapting to climate change [26, 27]. SSP2 represent a world where social, economic, and technological trends follow 'the-middle-of-the-road' path and do not shift markedly from historical patterns. To explore the impact and interactions between the three SDG7 targets, we design four additional scenarios as described below. Table 1 presents data for relevant indicators in the reference year and the most recent data. The targets and indicators for the scenario analysis are discussed in the SI.

Table 1: Input data for various indicators in 2010 & 2018

Indicator / **Year**	**Residential FEC (PJ/year)**	**Population (Million people)**	**Household energy intensity (GJ/ capita)**	**Share of Renewable energy in FEC (%), the bracket shows the share excluding trad. biomass**	**Population with access in 2018 (%)**	
					Electricity	***Cleaner cooking energy***
2010	9163	879	10.4	88 (9)	33	15
2018	10665	1080	9.9	81 (14)	45	29

In the *Universal access scenario (UNIV-ACC)*, all households get access to electricity and clean cooking by 2030. The efficiency improvements and renewable energy adoption follow the BASELINE trend. In the IMAGE-TIMER, household electricity demand is based on historical relationships between income and energy demand as discussed in van Ruijven, Schers [28]. In MESSAGE-Access, electricity demand is based on the bottom-up estimations from national surveys considering the 2030 projected income and population distribution. Clean cooking solutions include improved and advanced biomass-cookstoves[1], LPG, (liquid) natural gas, biogas, and electricity.

The *Universal access and energy efficiency scenario (ACC-EFF)* achieves both the energy efficiency and universal access target by 2030. Based on the results of previous studies [29-31], a target improvement in household appliance efficiency by 2030 is imposed, in combination with the

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[1] MESSAGE-Access only has two classes of biomass cookstoves, traditional and improved.

universal access target. This development happens independent of the renewable energy target that follows the BASELINE trend. The SI presents targets for household efficiency improvements.

In the *Universal access and renewable energy scenario (ACC-REN)*, the access target is achieved along with the renewable energy target. For our analysis, we exclude traditional biomass from renewables because it is unclear what percentage of traditional biomass should be considered renewable owing to unsustainable harvesting practices [32-34]. Besides, the dominance of traditional biomass-cookstove use in large parts of SSA inflates the shares of renewable energy if traditional biomass would be included. Moreover, substituting inefficient biomass-cookstoves with modern forms of renewables-based cookstoves would result in a decline in the shares of renewable sources in FEC. Efficiency improvement under this scenario follows the BASELINE trend.

The final scenario is the *Universal access, energy efficiency and renewable energy scenario* (ACC -REN-EFF), in which universal access to clean and modern energy is accompanied by improved energy efficiency and a higher share of renewables in the energy system. Table 2 provides a summary of the scenarios.

Table 2: Scenario framework

X = BASELINE trend

√ = Target achieved by 2030

Scenario	Description	Targets achieved		
		Universal access	Efficiency	Renewable energy share
BASELINE (SSP2)	Autonomous efficiency improvements, business-as-usual Renewable energy technology deployment and business-as-usual energy access rates	x	x	x
UNIV-ACC	Universal access to clean and modern energy is achieved under autonomous efficiency improvements and business-as-usual Renewable energy technology deployment	√	x	x
ACC-EFF	Universal access and enhanced energy efficiency improvement policies under business-as-usual Renewable energy technology development	√	√	x
ACC-REN	Universal access and renewable energy target are achieved under business-as-usual energy efficiency developments	√	x	√
ACC-EFF-REN	Universal access, enhanced efficiency improvements, and doubling the rate of Renewable energy technology deployment policies	√	√	√

3. Results

3.1. *Trends in access to clean fuels*

The number of people without access to electricity remained constant between 2010 and 2016, at about 600 million [10], as the electrification rate was similar to the population growth. The number of people lacking access to clean cooking fuels has increased between 2010 and 2018 as the rate of progress was outpaced by population growth [35]. IMAGE-TIMER and MESSAGE-Access show a considerable improvement in access to both electricity and clean cooking in BASELINE. However, this still falls short of the universal access target. The rapid pace of population growth, the modest increase in income, inadequate infrastructure investment, and the high cost of acquiring and operating modern fuel cookstoves limit the progress. IMAGE-TIMER projects that 80% of those who use biomass continue to depend on traditional stoves in 2030. MESSAGE-Access, on the other hand, projects that, with declining cost of technologies and increasing income, 80% are able to afford switching to more efficient biomass cookstoves by 2030. these are still not advanced cookstoves, thus the health benefits are limited. Around 350 million people use either gas or electric stoves for cooking in 2030 under BASELINE, however the share of these two differ across the models (Figure 1). These results are in line with those from the IEA [35] that estimate that 530 million people will lack access to electricity in the Stated policy scenario (scenario based on current and announced policies).

The UNIV-ACC scenarios reach the universal access targets by definition. The way full access is achieved, however, differs between the scenarios. In IMAGE-TIMER, electricity, natural gas, LPG and biogas play roles together with improved and advanced biomass-cookstoves. In MESSAGE-Access, clean cooking is provided primarily through advanced biomass-cookstoves and electricity, with LPG playing a limited role. Under UNIV-ACC, 600-800 million people rely on solid biomass, mostly charcoal and pellets, for cooking in improved and advanced cookstoves. Increased efficiency, improved consumer awareness, innovative financial schemes and reliable supply of modern fuels could further increase the attractiveness of electric and gas cooking. IEA [35] projections also shows that 600 million people rely on solid biomass in improved cookstoves under the Africa Case scenario (built on the visions of Agenda 2063 [36]).

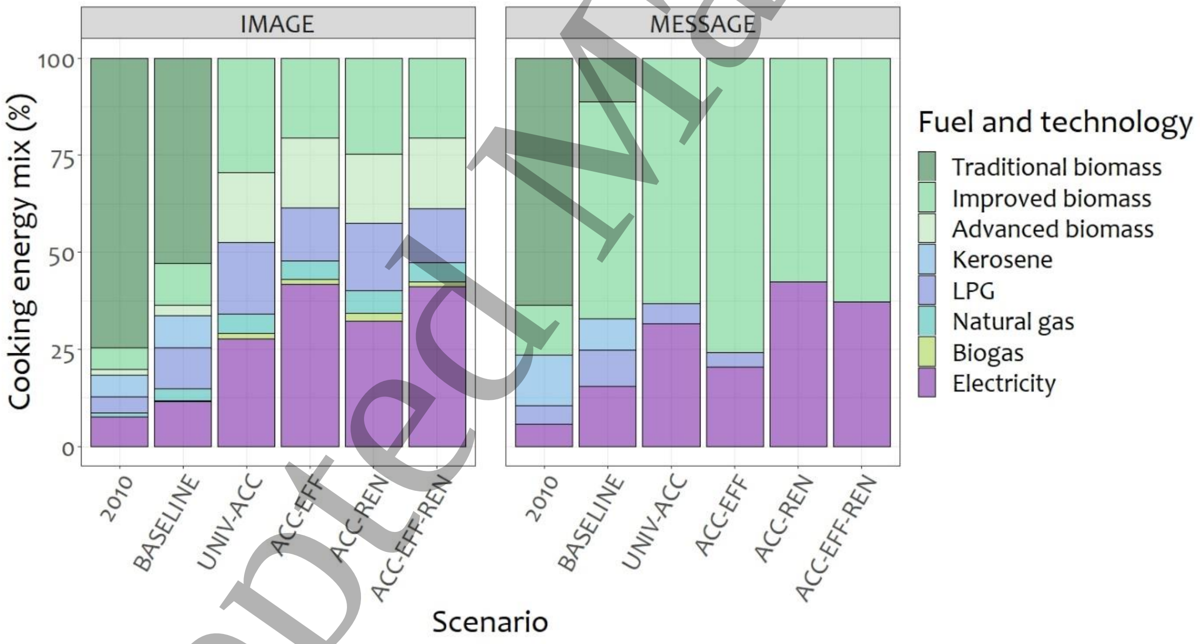

Figure 1: Cooking energy mix[2] in 2010 and 2030

3.2. Change in household final energy intensity

Household useful energy consumption is projected to increase as more households get access to electricity and the ownership of appliance grows. That increase was very small between 1990 and

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[2] Biomass includes both firewood and charcoal use

2010, as FEC increased by around 80% and population by 70%. The dominant energy use in the residential sector in SSA in this period was cooking and this will remain so in the coming decades.

Under BASELINE, FEC per capita remains constant in IMAGE-TIMER (see

Figure 2). This can be explained by the rapid efficiency improvement in cooking technologies, a switch from traditional to modern fuels, and constant useful energy demand for cooking. MESSAGE-Access projects a 60% increase in per capita energy consumption by 2030 relative to 2010, driven mostly by large increases in the uptake of appliances and some increase in cooking energy demand.

In UNIV-ACC, a complete phase-out of traditional biomass-cookstoves and a growing share of modern fuels in the cooking energy mix result in lower energy demand in IMAGE-TIMER. In contrast, in MESSAGE-Access, the efficiency gains are countered by a growing energy demand. As a result, total residential FEC under UNIV-ACC scenario declines (10MJ/capita) in IMAGE-TIMER but more-than doubles in MESSAGE-Access (29 MJ/capita) relative to 2010 (13MJ/capita). FEC declines by around 10% relative to 2010 in the Africa Case in IEA [35] amid efficiency improvements and the rapid displacement of (traditional) biomass in cooking.

Additional energy efficiency improvements in ACC-EFF provide large savings with a potential to reduce per capita energy consumption by 6-25% relative to UNIV-ACC. These savings are achieved by implementing efficient technologies that are already available on the market. Specifically, for IMAGE-TIMER, the largest efficiency gain comes from the halting of traditional biomass-cookstoves. The total saving in electricity consumption under ACC-EFF could reach up to 290 TWh by 2030, which brings down peak load allowing lower system capacity requirements for decentralised renewable-based energy systems. Both models show lower energy demand per capita under ACC-EFF-REN relative to UNIV-ACC reflecting the synergetic relationships of the targets.

With increasing income from 2010 to 2030, there is already a large shift from traditional biomass use to improved biomass use in MESSAGE-Access in BASELINE (Figure 1). Cooking energy demand remains similar between UNIV-ACC and ACC-EFF as the large efficiency gains together with rapid decline in price makes improved cookstoves a better alternative to modern fuels. IMAGE-TIMER show additional saving in cooking in ACC-EFF relative to UNIV-ACC driven by large gains from rapid efficiency improvements in biomass and modern fuel cookstoves.

The additional efficiency gain in ACC-EFF-REN can be as high as 25% relative to UNIV-ACC. However, in MESSAGE-Access, the savings made in cooking energy are countered by strong growth in appliance ownership. Specifically, the percentage of households possessing basic appliances such as televisions, and refrigerators doubles between 2010 and 2030. For other appliances with very low penetration in 2010, such as air conditioners or washing machines, there is a sizeable six-fold increase. In IMAGE-TIMER, ownership of appliances remains low as the average GDP per capita PPP remains under 4000 USD in SSA (excluding the Republic of South Africa).

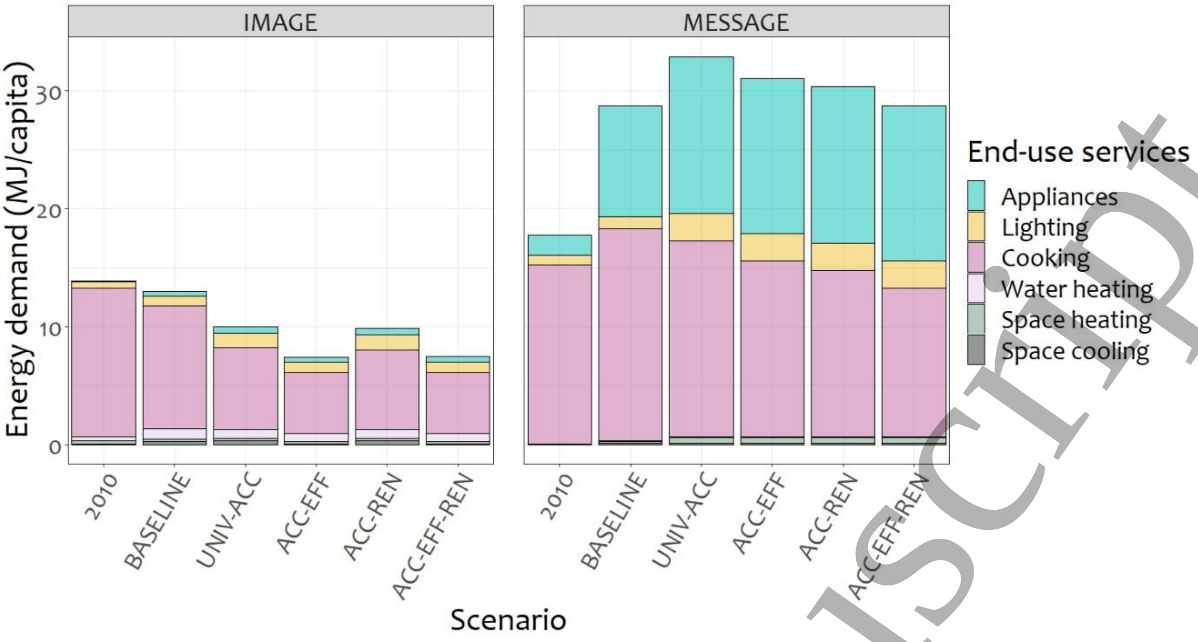

Figure 2: Per capita FEC for residential end-use services in 2010 and 2030

3.3. Renewable energy shares

The other SDG7 target is to substantially increase the share of renewable energy, i.e. solar, wind, geothermal, hydropower, bioenergy and marine sources, in FEC. Figure 3 shows the electricity mix and renewable energy shares in FEC. The energy system in SSA is dominated by bioenergy, with the exception of the Republic of South Africa. The rapid decline in cost of renewable energy technologies associated with accelerated global deployment has made them a cost-effective option for energy access in SSA. Under BASELINE, the share of renewables in the electricity mix increases from 24% in 2010 to 36-54% by 2030. Renewables as a share of final cooking energy use is projected to decline under BASELINE. Two factors explain this. The first is the efficiency gain in modern renewable energy technologies (including renewable electricity) and the second is the increasing share of gas replacing traditional biomass in cooking.

In ACC-REN, renewable energy shares increase by 5-35%-points relative to BASELINE. Electricity generation from solar and wind show large increase (26-40%), starting from a low base of a combined 1% in 2010. In ACC-EFF-REN, SSA's renewable energy share in electricity generation reaches 70-75% in 2030. Efficient appliances enable the deployment of solar home systems at a faster pace resulting in higher shares of renewable energy in this scenario.

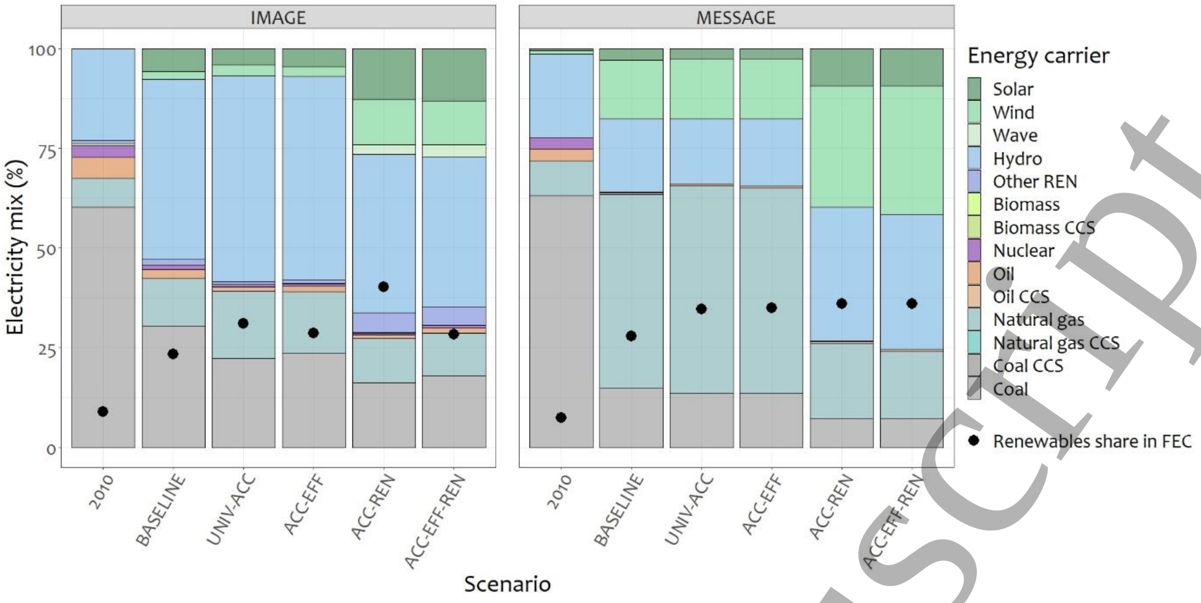

Figure 3: Electricity generation mix and renewable energy shares in FEC in 2010 and 2030

Under BASELINE, where there is no radical change in technological innovation or infrastructure development, solid biomass accounts for around two-third of the cooking energy demand in 2030. Electricity provides 11-16% of the cooking energy demand. With the assumption that 27-34% of the traditional biomass is harvested sustainably, we can conclude that 23-30% of the final energy used for cooking in SSA comes from renewable energy sources, including renewable-energy based electricity. To improve access to cleaner cooking solutions, avoid household air pollution related mortality and reduce emissions, cleaner cooking fuels and technologies such as efficient biomass-cookstoves, LPG and natural gas play a considerable role together with electricity and biogas. The share of renewable energy in cooking energy mix under ACC-EFF-REN scenario is between 64% (in IMAGE-TIMER) and 90% (in MESSAGE-Access) including the use of biomass in improved and advanced cookstoves.

The RE share in FEC (excluding traditional biomass) under BASELINE reaches near 25% in 2030, a similar projection as in the Stated policy scenario of IEA [35]. In UNIV-ACC, renewable shares are 22-31% in 2030, with IEA's Africa Case projection coinciding with the higher end of the range.

3.4. Investment requirements of providing universal access

BASELINE investments in electricity and clean cooking infrastructure is projected to be 11-19 billion USD annually between 2015 and 2030. Universal access requires an additional annual investment of 14-37 billion USD, as shown in Figure 4. ACC-EFF has lower investment requirements compared to UNIV-ACC. In IMAGE-TIMER, the lower investment requirement in ACC-EFF is a result of the high energy savings associated with increased appliance efficiency. When highly efficient appliances are used, the capacity requirements for off-grid systems reduce considerably, hence, reduce the capital cost of stand-alone and mini-grid systems. The relatively low household energy demand also leads to higher share of off-grid systems reducing required investments in transmission and distribution. ACC-REN benefits from lower renewable energy prices amid large-scale deployment of renewable energy technologies.

ACC-EFF-REN has a total investment requirement of 14-28 billion USD a year on average. The synergy between energy efficiency and renewable energy is demonstrated by the large avoided investment (up to 31%) in ACC-EFF-REN relative to UNIV-ACC. Higher renewable energy shares coupled with radical efficiency improvements reduces peak energy demand, hence lower capacity requirements. The electrification process largely favours renewable-based distributed systems, reducing grid losses and fuel transportation costs. The lower electricity demand together with the declining cost of renewable energy technology results in a cSG30mbined saving of up to a hundred billion USD by 2030. However, it also means that, even in the scenario with the lowest investment needs for universal access, a near-doubling of the BASELINE investment is required.

3.5. Energy use related residential sector emissions

Total residential energy-use-related emissions in 2010 amounted to 560 Mt CO_2e, including emissions from non-renewable biomass burning for cooking (Figure 4). Under BASELINE, residential GHG emissions grows by an annual average rate of 1-1.8% between 2010 and 2030 as growing energy demand counters autonomous efficiency improvements. The avoided emission in UNIV-ACC amounts to 23-26% compared to BASELINE owing to the halt in the use of traditional biomass-cookstoves. MESSAGE-Access shows a higher GHG emission in ACC-EFF than UNIV-ACC as higher efficiency and lower prices make charcoal a more attractive option than low emission fuels such as natural gas and electricity. Higher reduction in GHG emissions is achieved in ACC-EFF-REN through the increased implementation of decentralized electrification technologies (as a result of lower demand density), elimination of traditional biomass-cookstoves, increased deployment of improved and advanced biomass-cookstoves, and faster transition to modern fuel cookstoves. GHG-emissions in IMAGE-TIMER are in general higher than MESSAGE-Access as it considers that a third of the biomass is produced unsustainably resulting in a net-emission.

4. Discussion

This paper analyses synergies and trade-offs between universal access to clean and modern energy, higher energy efficiency, and increased renewable energy deployment in SSA. Using two distinct model frameworks allows us to capture uncertainties arising from different model structures and data on energy by end-use, which has so far been rarely explored in the literature.

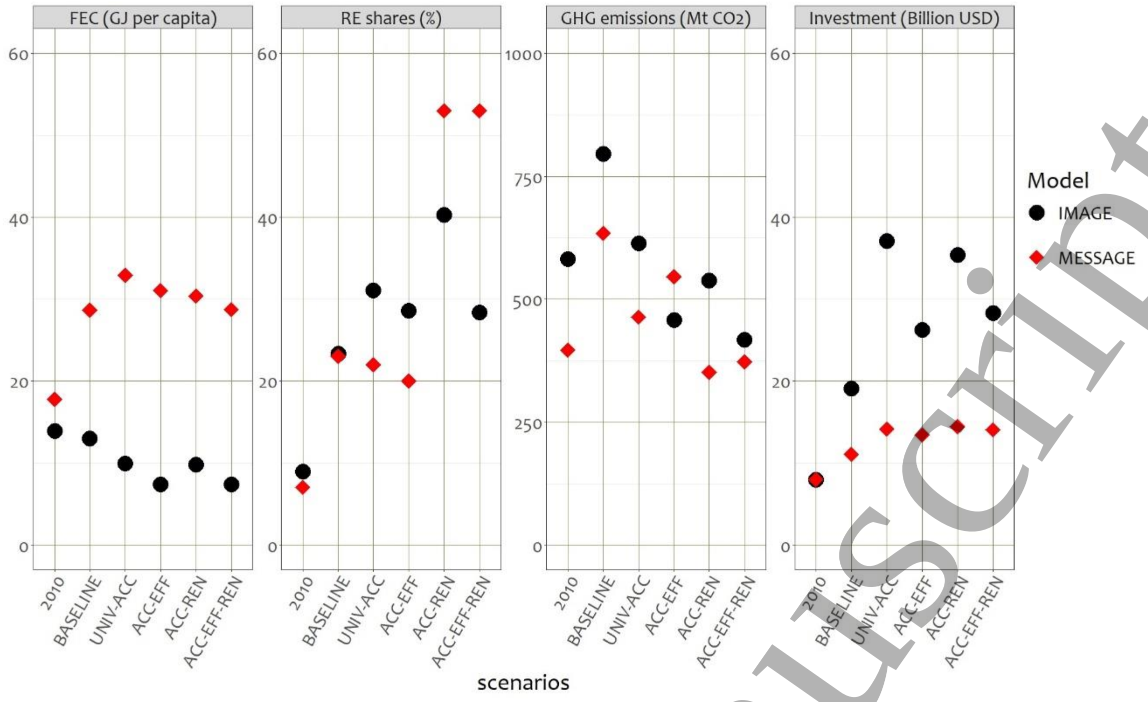

Figure 4: Final energy consumption, GHG emission, investment and renewable energy share in 2010 and 2030

Figure 4 summarises the results. Overall, the results depict the synergistic relationships between the three targets, so that our integrated scenario results in a lower FEC, lower GHG emissions, and lower investment needs relative to pursuing only the universal access target. This overall trend is consistent in the results from both models employed. There are, however, also important differences between the models, which reflect the methodological differences between the models and limitations in the availability of reliable historic data on energy by end-uses.

In this work, our focus is on household energy demand and does not consider demand for productive uses or other sectors of the economy. If those are considered, the demand density could increase, improving the financial viability of on-grid electrification. However, the decision to include or not include productive uses requires a trade-off between having access to electricity through quick and cost-efficient systems for low-demand density settlements that don’t meet the needs of most productive appliances, and high-quality on-grid connections that can provide electricity for productive uses but are slow to arrive, unreliable, and at times expensive. Our analysis also does not address any existing institutional, governance or financial barriers for energy efficiency or for renewable energy technology deployment. Literature suggests that these can be significant and future work could explore these barriers and means to overcome them in depth.

5. Conclusions

The results of our analysis provide some policy-relevant insights and conclusions, which we discuss here.

Our results show that integrating energy access, energy efficiency and renewable energy policies has several benefits . Integration stimulates the expansion of energy services while reducing the investment requirements and the impact on the climate. Higher energy efficiency improvements allow for providing a wide range of services with distributed systems, while distributed renewable energy expansion reduces conversion and transmission losses. Policies to expand generation and transmission capacities should consider efficiency improvements to avoid unnecessary extra capacity and save large amounts of hard needed finance. As end-use energy requirements decrease, the opportunity for low-energy density renewable sources to meet energy needs increases; thus, targets to increase the renewable share of total energy consumption can be achieved more expeditiously with added energy efficiency measures. With lower cost of end-use service delivery, money saved can be used to finance additional efficiency improvements and/or in the deployment of renewables.

There is a large potential for efficiency improvement in SSA despite the relatively low level of energy consumption. Cooking in SSA is a very energy intensive end-use activity driven by the widespread use of inefficient traditional biomass-cookstoves. Similarly, air conditioners, refrigerators, and other household appliances sold in SSA are typically far less efficient than most available units on the market. Large-scale deployment of the best available technology (efficient household appliances and equipment) could help deal with the growing demand for residential energy services in SSA. This can also enable the use of mini-grid and stand-alone systems to provide energy beyond lamps and radios, to meet demands for cooling, heating, and electric cooking services. It also creates opportunities for companies and consumers alike while decreasing the need for expensive peak capacity. This, however, requires designing and enforcing of national standards and labelling for household appliances and equipment efficiency.

The energy saving achieved through integration of policies leads to lower investment requirements for energy access and considerably lower energy related residential emissions by 2030. The saving achieved in FEC result in lower requirements for energy supply while helping households reduce their energy expenditure. The average annual capital investment for energy infrastructure and annual operation and maintenance expenditure could be up to 30% lower compared to the UNIV-ACC scenario. Similarly, integrating the three policies could reduce the annual energy-use-related residential emissions by a third relative to the UNIV-ACC scenario. The emission reduction is largely attributed to the efficiency improvements in biomass-cookstoves and a switch to modern fuels, including LPG, natural gas and electricity, for cooking. However, providing access through the deployment of more efficient technologies can be more expensive. Thus, targeted policies, innovation, and financing will be needed to achieve wide-scale deployment of efficient equipment and appliances.

Acknowledgements

The research presented in this paper was mainly funded by the European Horizon 2020 research programme, European Union, as part of the CD-LINKS project (Linking Climate and Development Policies-Leveraging International Networks and Knowledge Sharing) under grant agreement No 642147. The work also benefitted from funding by the Dutch Ministry of Foreign Affairs, the Netherlands, through its Directorate-General of Trade and International Cooperation.

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