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The effect of African growth on future global energy, emissions, and regional development

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SUMMARY Today Africa is a small emitter, but it has a large and faster-than-average growing population and per capita income that could drive future energy demand and, if unconstrained, emissions. This paper uses a multi-model comparison to characterize the potential future energy development for Continental and Sub-Saharan Africa under different assumptions about population and income. Our results suggest that population and economic growth rates will strongly influence Africa's future energy use and emissions. We show that affluence is only one face of the medal and the range of future emissions is also contingent on technological and political factors. Higher energy intensity improvements occur when Africa grows faster. In contrast, climate intensity varies less with economic growth and it is mostly driven by climate policy. African emissions could account for between 5% and 20% of global emissions, with Sub-Saharan Africa contributing between 4% and 10% of world emissions in 2100. In all scenarios considered, affluence levels remain low until the middle of the century, suggesting that the population could remain dependent on traditional bioenergy to meet most residential energy needs. Although the share of electricity in final energy, electric capacity and electricity use per capita all rise with income, even by mid-century they do not reach levels observed in developed countries today.

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1. INTRODUCTION

Today, Africa is a small contributor to global emissions. In 2009, continental Africa accounted for 3.2% of global CO_2 fossil fuel emissions and Sub-Saharan Africa for less than 1% of global emissions (IEA 2010). Emissions are low because economic activity is smaller than in other regions and most of the population still lacks access to electricity and clean-burning fuels (Pachauri et al. 2013). Currently, Africa produces only 4% of global Gross Domestic Product (GDP) (Newell and Iler 2013) and it uses only 5.9% of the global final energy (IEA 2010). However, African population could grow significantly in the future and, by 2100, more than 25% of the world's population could live there (UN Population Division 2009). By dint of sheer numbers, Africa could become a place to be reckoned with. Africa's future energy use and share of global emissions will depend on socioeconomic, technical, and political factors that will shape its energy intensity of GDP and the carbon intensity of energy. Economic growth is only one face of the medal. Consider for example France and the United States. They have similar per capita income, but per capita emissions in the United States are three times those of France. This difference is driven by a number of factors, including the heavy reliance on nuclear power in France, the preference for big cars, and the very low efficiency levels of buildings in the US. Which development pathway Africa follows will influence its emissions and could potentially impact global emissions due to the projected size of Africa's population. Given the very low level of per capita income in Africa today, many different development pathways are possible and Africa's emission pathway over the coming century remains highly uncertain.

Economic growth is, however, a very approximate indicator of human well-being and development. Future development in Africa will necessitate extending access and supplies of modern energy to most of its population. Sub-Saharan Africa has lagged far behind the rest of the world in providing its population with access to electricity (only 14% of rural and 63% of urban residents were electrified in 2010) and modern fuels (over 80% still rely on traditional solid fuels for cooking) (WB, 2013). Evidence of the pivotal catalytic role of access to adequate, affordable, reliable and suitable energy types for lifting people out of poverty and enhancing their welfare is irrefutable (Cabraal et al., 2005; Desai et al., 2004; Modi et al., 2005; Pachauri et al., 2012).

The linkage between economic activity, energy use, and emissions has been extensively analyzed globally and for several key regions, such as the United States, Europe, China, and India (Nakicenovic and Swart 2000; Blanford et al. 2009; Blanford et al. 2012). A similar assessment is lacking for Africa. Indeed, very few future scenarios exist for the African continent. They either focus on selected countries (e.g. South Africa, see Winkler et al. 2011; Erickson et al. 2009, or Eritrea, see Buskirk 2006), or when larger in scope, on the first half of this century (EIA 2013, IEA 2010, IEA 2012, MIT 2012). Modeling comparison exercises, such as the Special Report on Emissions Scenarios (Nakicenovic and Swart 2000) and the Energy Modeling Forum studies (see Clarke et al. 2009, for example) have also never focused on this region and commonly Africa has either been grouped with other large regions or only included in world totals. Bigger economies have attracted the attention of regional modeling comparison exercises, such as Europe (Böringher et al. 2009), USA (Clarke et al. 2007; Fawcett et al. 2009), China and India (Calvin et al. 2012). Admittedly, the lack of scenarios and historical data for some African countries makes the process of model calibration and evaluation more challenging for this region.

This paper fills this gap by using a multi-model comparison to explore possible population and economic growth pathways for Africa throughout the century. It looks at how these factors will transform the energy system and emissions, in four energy-economy models with different views about future technological development, opportunities, and economic structure. The paper also explores to what extent future economic growth could improve access to modern forms of energy in the region and whether climate policy can hasten or hinder this. The paper is organized as follows. Section 2 describes the assumptions regarding key drivers of the African economy, population and GDP. Section 3 discusses the future trends of energy and emissions without and with climate policy. Section 4 uses the baseline and policy results discussed in the two previous sections to assess the effects on energy-related development indicators. The final section concludes with key findings of this study and identifies areas for further research.

2. POPULATION AND ECONOMIC GROWTH IN THE AFRICAN ECONOMY

We analyze future pathways for Africa by comparing the results of the four models that participated in the "Roadmaps towards sustainable energy futures" (RoSE) project: GCAM (Calvin et al. this issue), IPAC (Jiang this issue), REMIND (Bauer et al. this issue) and WITCH (De Cian et al. this issue). All four models represent Africa, though with different geographical aggregations. In REMIND and WITCH, Africa represents Sub-Saharan Africa, while in GCAM and IPAC it represents the whole continent, including North Africa and South Africa[1].

The scenarios explored in this paper have been developed within the framework of the RoSE project (see Kriegler et al. this issue). We focus on four baseline and four policy scenarios that allow examining the role of economic and population growth[2] under two policy regimes (no-policy baseline and 550 ppmv CO_2 equivalent stabilization target). Three of the sets of the economic-population growth assumptions, namely slow, medium, and fast economic growth (respectively BAU FS Gr, BAU DEF and BAU SL Gr Scenarios for baseline, and 550 FS Gr, 550 DEF, and 550 SL Gr for policy) assume medium population. In this case, African population stabilizes after 2050 and in 2100 accounts for 28% of the world's population (87% of which live in Sub-Saharan Africa)[3]. The fourth set of assumptions represents a pessimistic pathway characterized by very low per capita

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[1] The individual models use different criteria to map countries to regions. GCAM and IPAC focus on geographic proximity and as such all regions include contiguous countries. REMIND and WITCH aggregate countries to regions based on their development and therefore include North Africa with Middle East and South Africa with Korea and Australia (WITCH) and with the Rest of the World (REMIND).

2 The GDP per capita scenarios have been developed using the methodology described in Hawksworth (2006). The methodology is based on a Solow-Swan model with capital and quality adjusted labor as input factor and exogenous assumption about future Total Factor Productivity (TFP) growth. Population scenarios are from the UN, historic GDP and investment information are from the Penn World Tables and data on education levels are from Barro and Lee (2010). Variations in the speed of growth are obtained by varying the TFP growth of the US. The other regions are assumed to converge to the technology frontier at a slow or fast speed. All models used in the comparison exercise, represent economic entities in Market Exchange Rate (MER). As a consequence, the Purchasing Parity Power (PPP) GDP per capita scenarios have been converted into MER using a projection of the PPP to MER ratio for the 21st century.

[3] As noticed in other studies for Africa, this share is significantly larger than the expected share of China or India (Cilliers et al. 2011).

income, driven by high population, slow growth and slow convergence across world regions (BAU HI Pop Scenario for baseline and 550 HI Pop for policy). The BAU HI Pop baseline echoes a vision of a fragmented world, where extreme poverty, regionalism, and high population could increase the vulnerability of economies heavily dependent on agriculture, making them more vulnerable to climate change impacts. It is important to note that these scenarios were designed to explore the sensitivity of energy and emissions to population and GDP assumptions, not to explore uncertainty. Therefore results presented in this paper should not be construed as a full uncertainty range.

The different models implemented the scenarios by modifying exogenous parameters in such a way to replicate the specified assumptions for population and economic growth (see Table 1)[4]. Specifically, in all models population was exogenously set to match the figures provided in the 2008 Revision of the UN Population Prospects (UN 2009). GDP per capita trajectories were replicated by adjusting the productivity of all production factors (WITCH) or of labor (REMIND, GCAM, IPAC). Further, fossil fuel resource availability and extraction costs have also been harmonized, but no attempt has been made to harmonize energy intensity. In the next section we explore the implications of baseline scenarios on the future energy system and emissions. We also examine the implications of limiting CO_2-equivalent concentrations to 550 ppmv in the different population and economic growth scenarios.

[4] Table 1 shows the results of scenario implementation in the individual models.

3. FUTURE ENERGY SYSTEMS AND EMISSIONS

3.1 FUTURE TRENDS IN ABSENCE OF CLIMATE POLICY

Economic growth will drive Africa's demand for energy. However, despite the harmonization in GDP per capita and population, models foresee a broad range in baseline final energy and CO_2 emissions (Figure 1), even when accounting for different geographical definitions of Africa. Final energy consumption growth rates (2005-2100) vary between 1.2% (BAU HI Pop in WITCH) and 2.4% (BAU FS Gr in REMIND) per year in Sub-Saharan Africa and between 1.5% (BAU HI Pop in IPAC) and 2.3% (BAU FS Gr in GCAM) per year in Continental Africa. The resulting variation in energy consumption in 2100 indicates that models embed very different views about the relationship between income and energy services, energy efficiency, and the cost and availability of different fuel carriers and technologies, and their evolution throughout the century. In all models, the BAU HI Pop Scenario has the lowest final energy consumption. Although this scenario has approximately one billion more people in 2100 than the other scenarios, GDP per capita is significantly lower (see Table 1). The latter effect dominates, resulting in lower energy consumption.

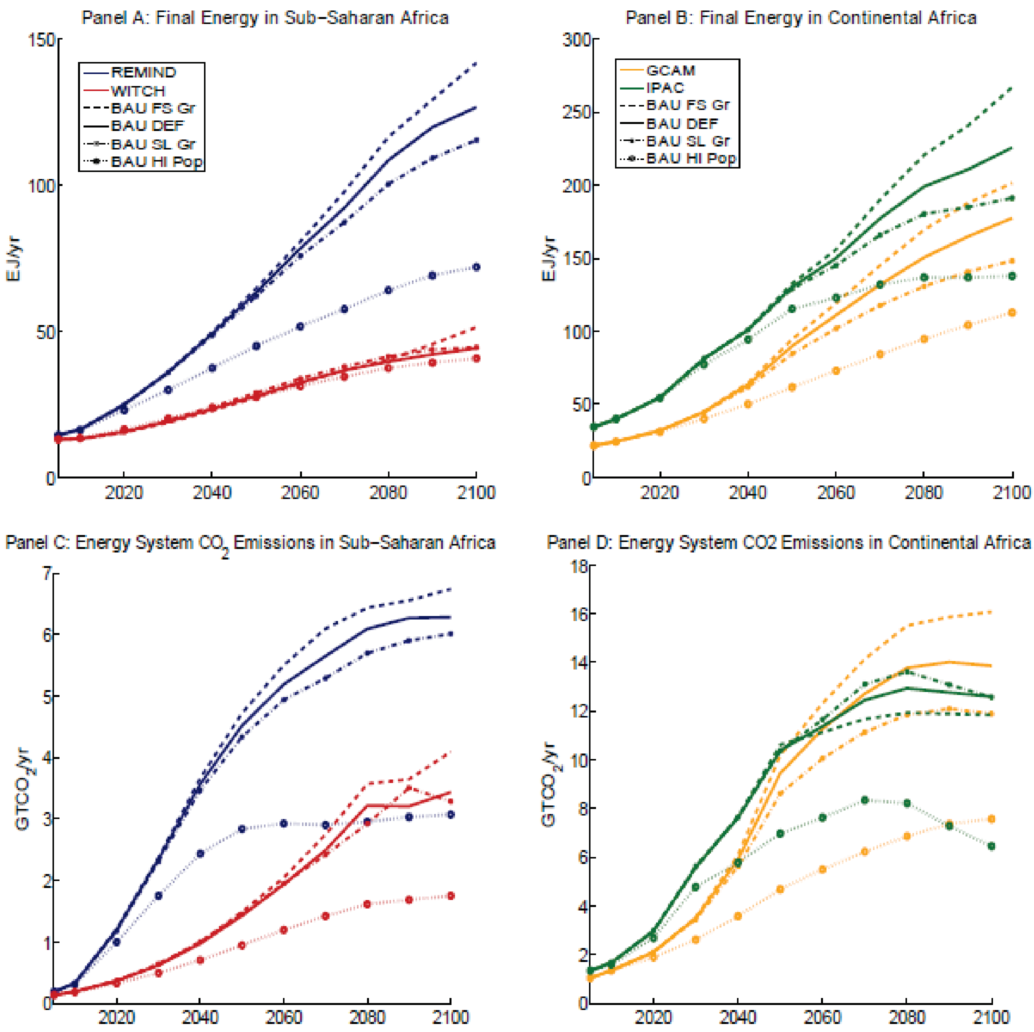
Table 1: GDP per Capita (Growth Rate and Absolute) across Models and Scenarios[5]

		GDP per capita Average annual growth rate 2005-2100			
		Slow (BAU SL Gr)	Medium (BAU DEF)	Fast (BAU FS Gr)	HI Pop
Continental Africa	GCAM	2.7%	3.1%	3.5%	1.6%
	IPAC	2.6%	3.0%	3.3%	1.5%
Sub-Saharan Africa	REMIND	3.2%	3.6%	4.0%	1.7%
	WITCH	3.3%	3.6%	4.1%	1.8%
		GDP per capita in 2050 (1000 2005$ per person)			
		Slow (BAU SL Gr)	Medium (BAU DEF)	Fast (BAU FS Gr)	HI Pop
Continental Africa	GCAM	$4.7	$5.1	$5.4	$2.6
	IPAC	$4.5	$4.8	$5.0	$2.5
Sub-Saharan Africa	REMIND	$3.7	$3.9	$4.2	$1.6
	WITCH	$3.7	$3.8	$4.3	$1.7

[5] Using these assumptions, GDP in 2060 varies across scenarios from $8 and $18 Trillion, a range comparable to the other few projections available. For example, the African Development Bank optimistic scenario (AfDB 2011) foresees a GDP level in 2060 equal to US$17 Trillion at current market prices. The MIT Joint Program Energy and Climate Outlook 2012 projections for Continental Africa are very close to our Baseline Slow Growth Scenario (BAU SL Gr). In 2050, GDP per capita reaches 2004$1,949 per person, while population grows to 2,191 million (MIT 2012). It is important to keep in mind that these are projections in Market Exchange Rates and therefore underestimate future growth and income levels in Africa. Our numbers would be between 1.3 and 1.7 higher in PPP terms.

Energy system CO_2 emissions grow between 2.7% (BAU HI Pop in WITCH) and 3.8% (BAU FS Gr in REMIND) per year (2005-2100) in Sub-Saharan Africa and between 1.6% (BAU HI Pop in IPAC) and 2.9% (BAU FS Gr in GCAM) in Continental Africa. For three of the models, the BAU FS Gr Scenario has the highest CO_2 emissions in 2100, followed by BAU DEF, BAU SL Gr, and finally BAU HI Pop. In the case of IPAC, faster growth is associated to increased use of nuclear energy, both in absolute terms and percentage terms, and therefore lower fossil fuel use and lower emissions compared to the BAU SL Gr and BAU DEF Scenarios.

Figure 1: Final Energy and Energy System CO2 Emissions without Climate Policy



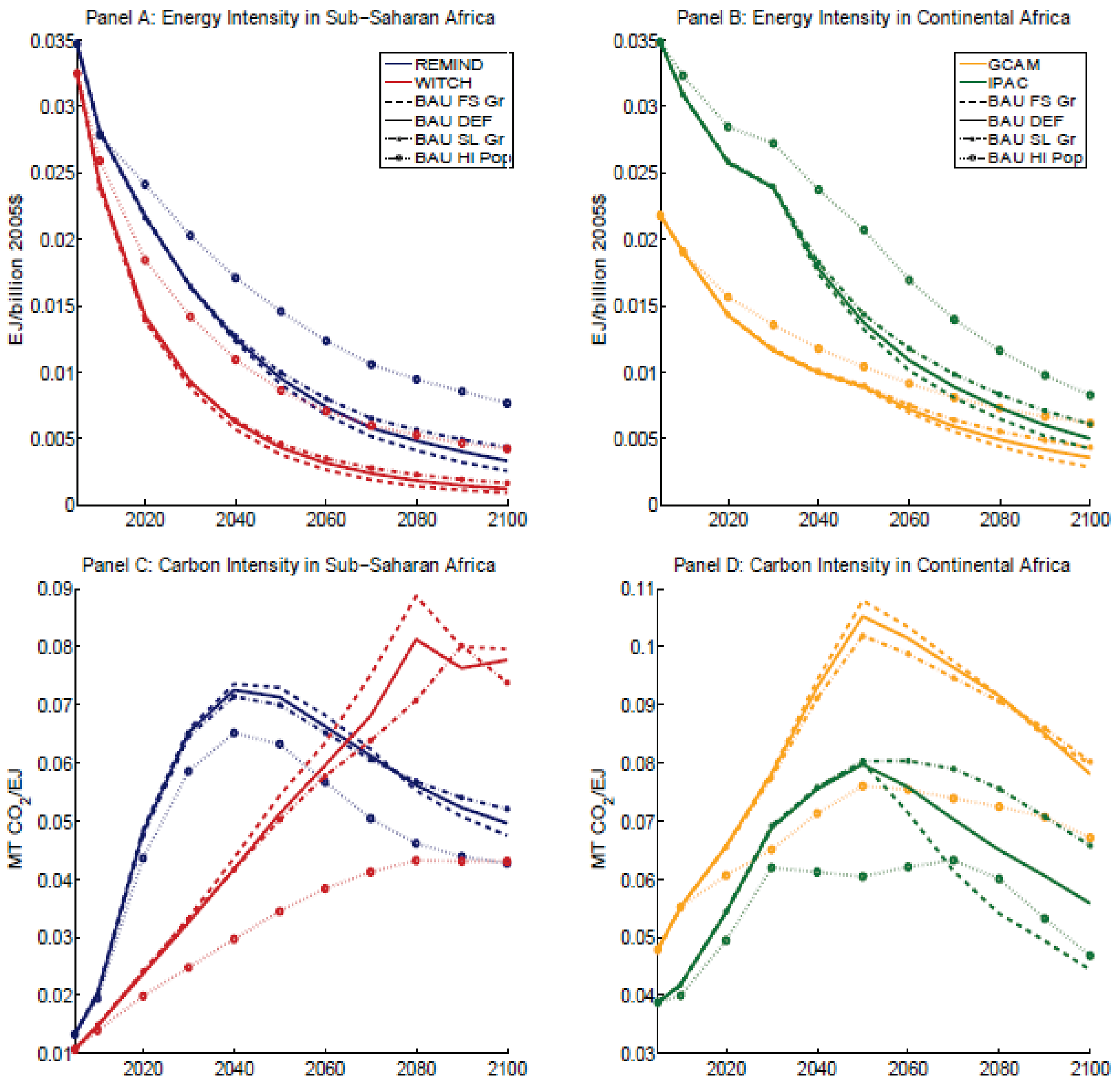
To help understand the differences in emissions across models, we use the Kaya identity (Kaya, 1990) to decompose emissions. The Kaya identity highlights the contribution of the drivers of population, GDP per capita, final energy intensity, and emissions intensity:

$$Emissions = Population \cdot \left(\frac{GDP}{Population}\right) \cdot \left(\frac{Final\ Energy\ Use}{GDP}\right) \cdot \left(\frac{Emissions}{Final\ Energy\ Use}\right)$$

Since the first two of these factors have been harmonized (see Table 1), all variation in emissions can be attributed to differences in energy intensity of GDP (Figure 2a,b) and to carbon intensity of energy (Figure 2c,d), which are technical factors reflecting different visions about technology and energy options for the African economy. African energy intensity varies significantly across models in absolute terms, but there is agreement on the relative trends with higher energy intensity improvements being observed in scenarios with faster growth. Changes in energy intensity reflect the substitutability between capital and energy and assumptions about energy efficiency improvements over time. These improvements are exogenous in all models[6], except WITCH where they are endogenously linked to R&D investments.

[6] In REMIND the efficiency parameters are assumed to change at the same rate as labor efficiency, plus an additional adjustment factor is applied that varies per region and final energy type and results in continuity of past trends and a converging behavior between regions (EJ/capita over GDP PPP/capita) (Luderer et al. 2013).

Figure 2: Energy Intensity and Carbon Intensity without Climate Policy



In contrast, carbon intensity is mostly affected by the composition of the energy mix (Figure 3 and Figure 1 in the Supplementary Material, SM). In most models and scenarios, we observe a shift away from traditional biomass[7] to more modern energy carriers and fossil fuels throughout the century (Figure 3). However, the degree of electrification, but also the employment of various fossil fuels in the form

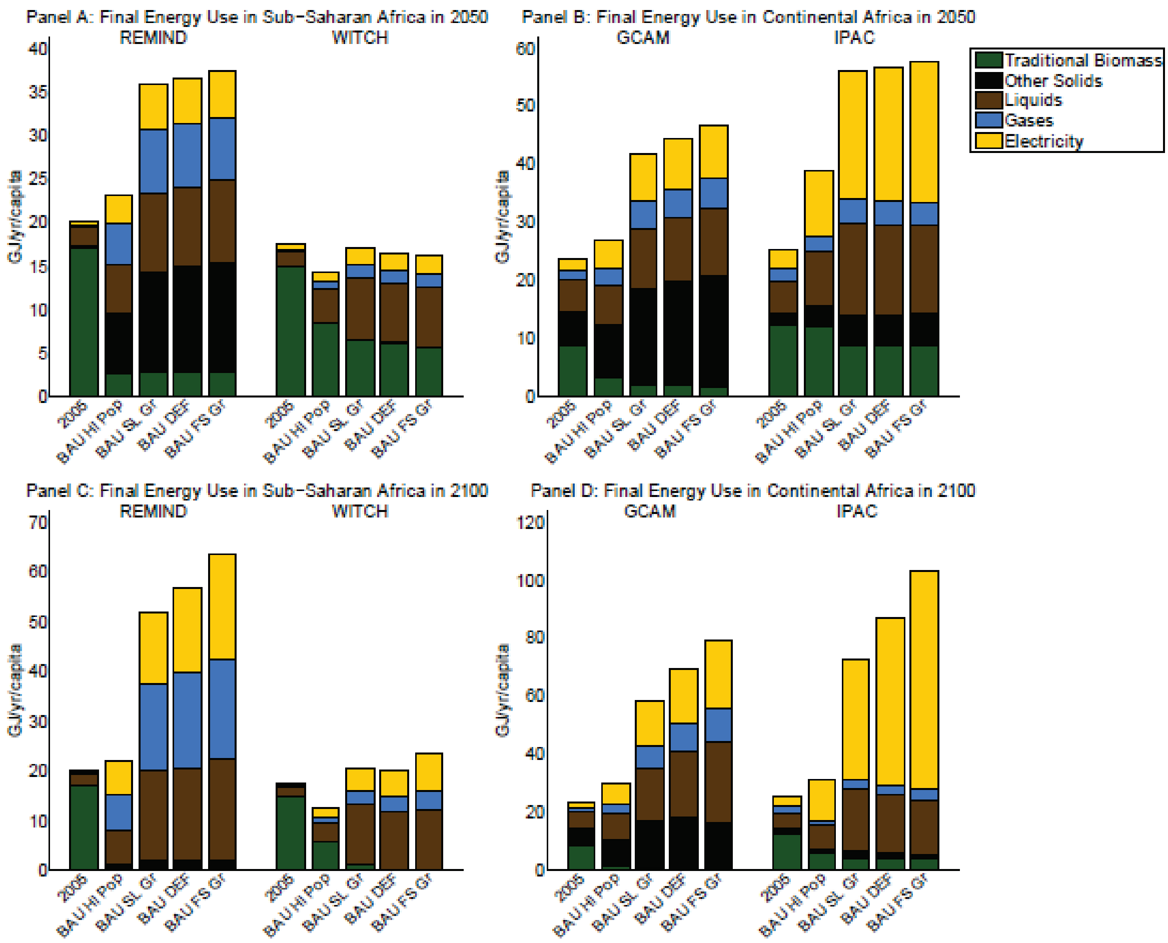
[7] Traditional biomass is usually defined as unprocessed fuelwood, agricultural residues, and animal dung, as well as charcoal, normally combusted on open fires or in very inefficient stoves. Traditional biomass is represented as a function of GDP per capita in the WITCH and GCAM models, and exogenous assumptions are employed in REMIND.

of liquids, solids or gases is very different across models. GCAM, IPAC, and REMIND, which show a sharp increase in carbon intensity in the first half of the century, feature a higher increase in final energy from coal (other solids), while in the WITCH model, traditional biomass continues to account for a large share of final energy. Solids use is largely reduced by 2100 in all models, and replaced to a large extend by electricity [8]. By the end of the century, models with lower carbon intensities (IPAC and REMIND) are associated to higher electrification rates. Differences in the sources of energy used for the production of electricity further contribute to differences in carbon intensity levels across models, with GCAM and WITCH relying more on fossil fuels, REMIND on greater deployment of solar [9] and IPAC on nuclear (SM Figure 1).

[8] Electrification rates are driven by numerous factors. Some mechanisms that influence electrification rates, e.g. in the case of REMIND, include a) possibility of substitution between transport energy, electricity, and non-electric energy for stationary end uses within the nested Constant Elasticity of Substitution production function, b) calibration of the energy efficiencies of the stationary electricity CES leaf, c) provision of energy through numerous competing technologies characterized by different efficiencies, lifetimes, investment costs, fixed and variable operation and maintenance costs, learning rates, etc.

[9] Reasons motivating differences in the deployment of solar and nuclear across models include a) in REMIND solar (and wind) technologies are characterized by endogenous technological change through learning-by-doing, where investment costs decrease by pre-specified rates for each doubling of cumulated capacity, b) solar is not considered in the WITCH model, c) in REMIND and IPAC a sharper increase of gas and coal prices in the second half of the century is observed.

Figure 3 : Final Energy Use per Capita in 2050 and 2100 without Climate Policy



Overall, carbon intensity appears to be mostly model-specific, and with the exception of IPAC, it shows very little variation with economic growth assumptions. Only the BAU HI Pop Scenario shows a lower increase in carbon intensity of energy. In IPAC, the BAU FS Gr Scenario has a strong decline in carbon intensity, due to the increased use of nuclear energy mentioned above. Compared to the global trends[10], in most scenarios African energy intensity declines faster than the world average, with the range varying between -3.6 and -1.3%. In contrast, the carbon intensity grows more rapidly than the world average in most models and scenarios. REMIND and WITCH, which represent Sub-Saharan Africa, show the largest rates of energy intensity reduction and of carbon intensity increase.

[10] Global energy intensity growth rates range between -2.2 and -1.1%, while carbon intensity rates range between -0.1 and 0.9%.

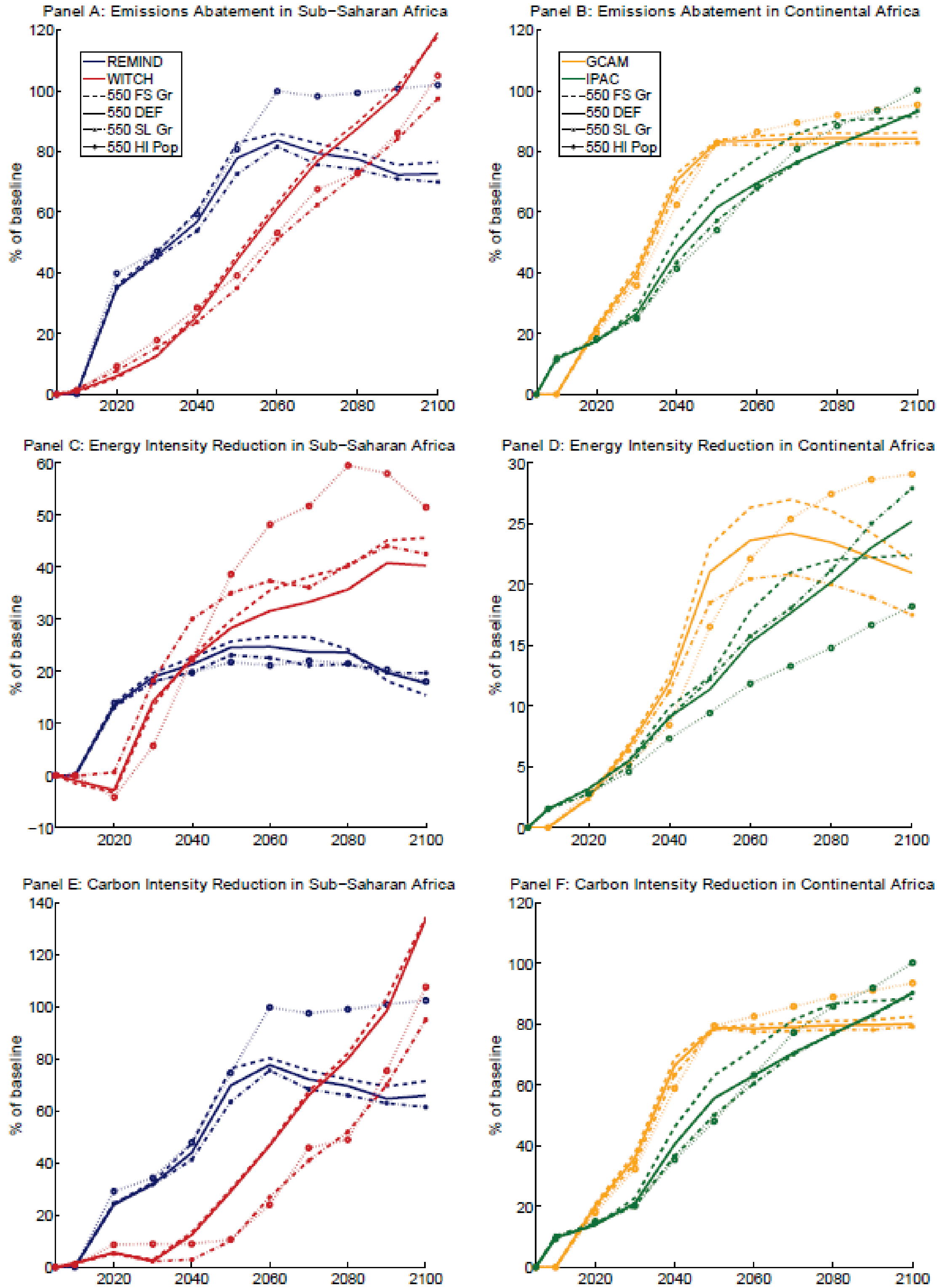
3.2 FUTURE TRENDS WITH CLIMATE POLICY

Future energy systems and emissions could follow a different pathway in the presence of Greenhouse Gas emissions (GHG) regulations or if Africa joined a global agreement that stabilizes GHG concentrations by the end of the century. The imposition of such a policy forces significant abatement in Africa (Figure 4a,b). At least 70% of emissions must be abated by the end of the century in all models and scenarios. Some models show more than 100% emissions reductions in a given year, indicating a heavy reliance on bioenergy in combination with CO_2 capture and storage (BECCS).

We use the Kaya Identity to isolate the contribution of reductions in energy use and of shifts in the fuel mix, and examine how climate policy modifies the change in energy intensity and carbon intensity (Figure 4c-f). The WITCH model reduces energy intensity significantly in response to a climate policy, while the other models only reduce energy intensity 20 to 30%. Differences in results across models are due to differing assumptions about (1) the availability of more energy efficient technologies and the presence of endogenous technical change, (2) the elasticity of demand, (3) the possibility to substitute energy with capital, and (4) the response of energy prices to climate policy. For example, GCAM is a technology-rich model with a low price elasticity of demand. With these assumptions, GCAM has a fairly low reduction in energy intensity. In WITCH, energy efficiency improvement is endogenously affected by R&D investments and climate policy, thus, setting a price on carbon induces an increase in those investments (see also De Cian et al., this issue).

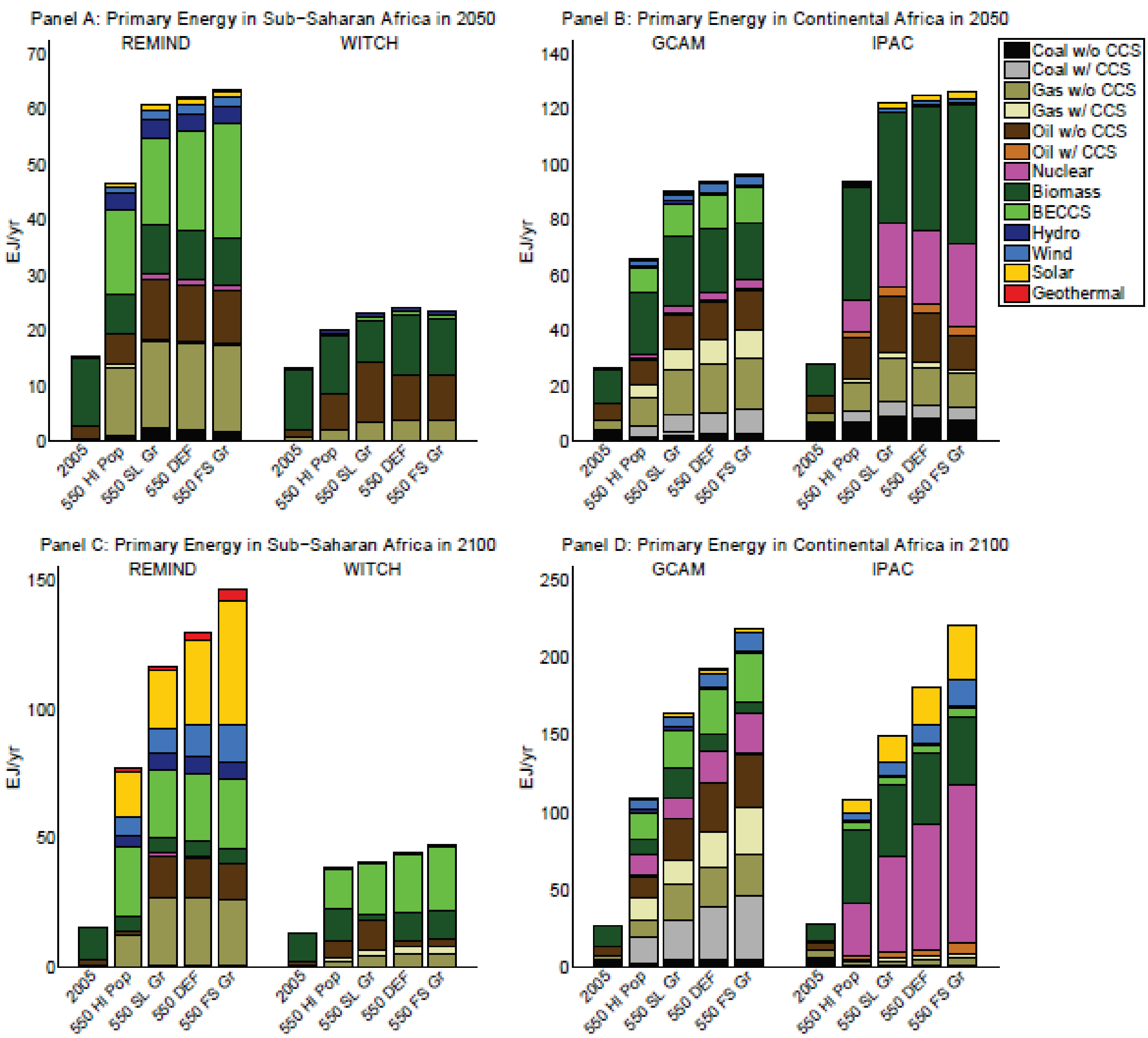
All models eventually reduce carbon intensity more than energy intensity, though with different time profiles. For example, WITCH points at the role of energy efficiency improvements in the short-term, while decarbonization plays a more important role in the long-run. This combination of energy efficiency measures and decarbonization is also due to the fact that some carbon free technologies are subject to endogenous learning and therefore are adopted more broadly in the long term when costs are lower. In contrast, GCAM and REMIND have more low carbon supply options, leading to a more significant reduction in carbon intensity than energy intensity

Figure 4: Reduction in Emissions, Energy Intensity and Carbon Intensity from imposing a Climate Policy



While all models reduce their use of freely-venting fossil fuels under a climate policy, the choice of low-carbon fuels to replace them varies across models and to a lesser extent across scenarios (Figure 5 and SM Figure 2). GCAM tends to deploy CO_2 capture and storage (CCS) technologies to decarbonize the energy system in Continental Africa, while IPAC relies on increased nuclear and bioenergy. In Sub-Saharan Africa, both models rely on the use of BECCS, in addition to the expansion of renewable energy sources in REMIND and energy reductions in WITCH, to meet climate policy goals.

Figure 5 : Primary Energy Use in 2050 and 2100 with Climate Policy



All models suggest that Africa has a large mitigation potential compared to the global average (SM Figure 3). In the WITCH and REMIND models, Africa has a large potential for BECCS enabling more stringent reductions than in other regions. GCAM has similar potential for low-carbon fuels as other regions. However, Africa is a rapidly developing region and the model assumes it is easier to build new low-carbon capacity in such a region than shutdown or retrofit existing capacity in more developed regions.

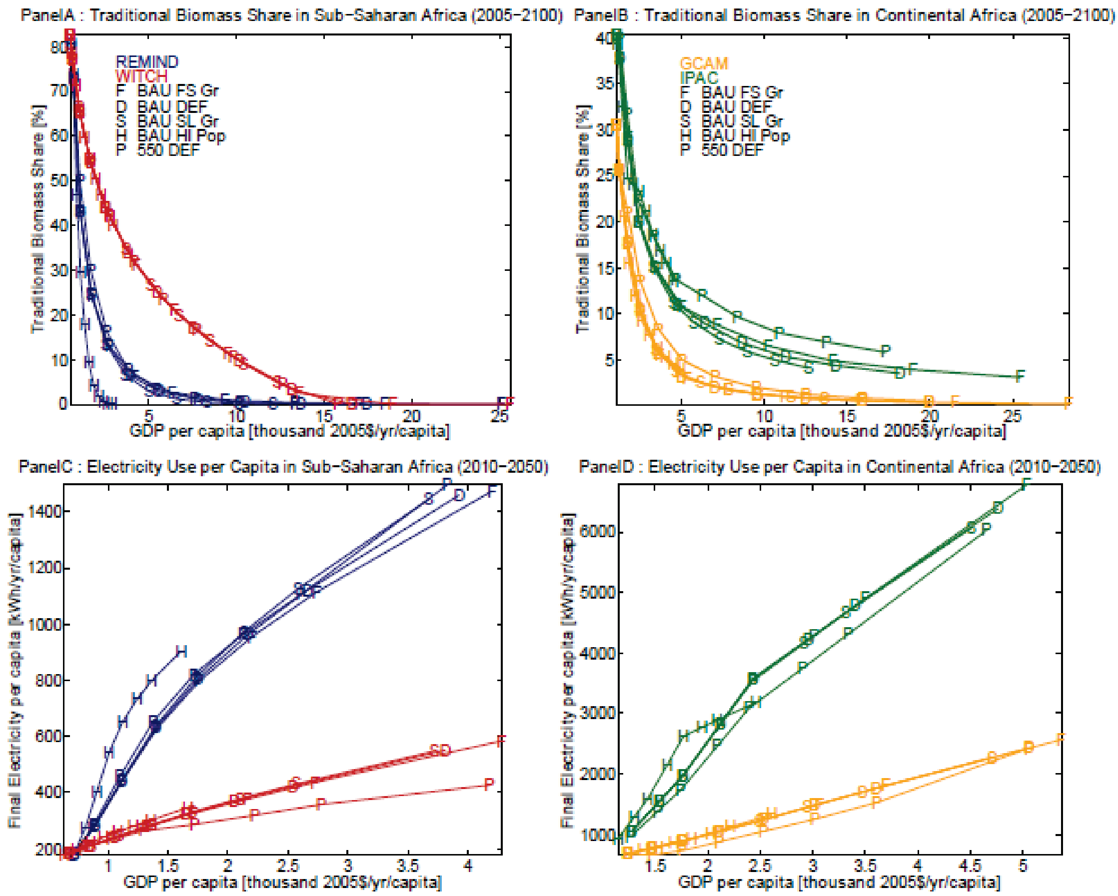
4. FUTURE ENERGY SCENARIOS AND IMPLICATIONS FOR DEVELOPMENT

In Africa, access rates to modern forms of energy are well below global averages and therefore improving energy access is a priority for the population of this continent. This section examines to what extent the baseline and policy scenarios, presented in the previous section, can achieve some development-related energy goals. Although none of the RoSE models is explicitly designed to address the linkages between energy and poverty or equity in development, and sector disaggregation and representation of socio-economic heterogeneity is limited, some useful indicators can be constructed. We analyze changes in the following indicators: i) share of traditional biomass in primary energy use, ii) average final energy use, iii) electric generation capacity, and average use, and iv) residential sector energy mix. These indicators are selected based on available model outputs and their relationship to development. We first discuss how these indicators relate to development, then assess how these vary across the scenarios, and finally examine what this could imply for future development in Africa.

4.1 SHARE OF TRADITIONAL BIOMASS

In most developed economies, industrialization was accompanied by an energy transition away from traditional biomass. For instance, in the case of the USA, biomass intensity in the economy was seen to decline exponentially with economic growth. Its share in primary energy dropped to under a third by the early 1900s, once average incomes reached about $5000/capita (Victor and Victor 2002). As traditional biomass use has adverse implications for human health and welfare, and is extremely inefficient (Pachauri et al. 2013), a transition away from it is desirable from a developmental perspective. This is indeed a common feature of all scenarios and models examined in this paper. Over time the share of traditional biomass declines. In 2005, biomass is the predominant energy source in all models, with a share varying from 80% in REMIND and WITCH for Sub-Saharan Africa, to 30-40% in GCAM and IPAC for the entire continent. Across all the models and scenarios, the share of primary biomass is projected to fall to below a third when income reaches a level of between $3600/capita and $4200/capita (approximately $10/capita/day and above) (Figure 6a, b). However, for the BAU HI Pop Scenario, average income is projected to stay below $5000/capita till 2040 and the share of primary biomass correspondingly high (even as high as 44% for Sub-Saharan Africa, according to the WITCH model). Imposing a climate policy, results in an even slower transition away from traditional biomass. This persistently high level of biomass intensity in the region, suggests that a large share of the population could continue to rely primarily on biomass to meet its residential needs for the next couple of decades.

Figure 6 : Traditional Biomass Share in Total Primary Energy till 2100 and Electricity Use per Capita till 2050



4.2 AVERAGE FINAL ENERGY USE

While there is no universally accepted minimum threshold of final energy use per capita deemed necessary for economic development, some early estimates set a threshold of 1 kW/capita or 31 GJ/capita/year (Goldemberg et al. 1985). More recently estimates in the range of 50–70 GJ/capita have been suggested as necessary to provide for basic human development (Nilsson et al. 2012; Smil 2003). Even if such a threshold exists, recent research suggests that this level may not be constant. Some decoupling with economic growth is expected over time, and the threshold may vary significantly across nations depending on which aspects of human development are considered (Steinberger and Roberts 2010). However, the exact welfare impacts of changes in average final energy use depend ultimately on how this use is distributed across a population. Across most models and all scenarios, average final energy use is projected to remain below 50 GJ/capita till 2050, far below the average in most OECD countries today (Figure 3). This level may not be inconsistent with achieving developmental objectives on the continent. However, achieving these goals is likely to be more challenging under the BAU HI Pop Scenario and the climate policy scenarios (SM Figure 2), since average final energy use in these cases is projected to be lower across all models.

In order to explore what the scenario projections might imply for the numbers of Africans that could remain below a threshold level of final energy use in 2030, we carry out a thought experiment based on an ex-post distributional assumption. We assume the income distribution in Sub-Saharan Africa follows the trend assumed by the Global Energy Assessment-Mix (GEA-M) scenario (Riahi et al. 2012). Further, we assume that final energy distribution mirrors this income distribution (see (Chakravarty and Tavoni 2013) for recent research that follows this approach). All the scenarios and models project a rise in average final energy use over time. However, under these distributional assumptions, 11%-27% of sub-Saharan Africans in 2030, and even as many as 12% by 2050 could have an average use that is below a threshold that meets even basic direct residential energy needs[11], unless dedicated policies that enhance equity are implemented.

4.3 ELECTRICITY CAPACITY AND AVERAGE USE

Energy in the form of electricity is crucial to modern life, as certain activities, like lighting, refrigeration, running household appliances, and operating equipment cannot easily use other energy forms. For this reason, access to electricity is considered an important indicator of modernization and development. Sub-Saharan Africa suffers acutely from a lack of access to electricity and poor quality of supply, where it does exist (Bazilian et al. 2012). Only a third of the region's population is

[11] We assume 5 GJ/capita of final energy is needed for meeting basic domestic cooking and electricity needs, as stipulated by the UN Secretary-General's advisory group (AGECC, 2010).

electrified even today (IEA 2012). Excluding South Africa, the entire installed generation capacity of Sub-Saharan Africa is about 40 GW, less than that in Mexico alone (EIA 2013b). Thus, a growth in installed capacity and electricity generation is critical to power development in the region (Eberhard et al. 2011). Pachauri et al. (2013) estimate that an additional 20 GW of installed capacity by 2030 would be required to provide basic electricity access to all households in Sub-Saharan Africa (420 kWh/year/household to meet basic lighting and minor appliance use). Bazilian et al. (2012) estimate that providing everyone in Sub-Saharan Africa (excluding South Africa) with moderate access (both for direct residential purposes and economy-wide productive uses) would require an installed generation capacity of about 374GW or an annual growth rate in capacity of 13% for the next 20 years. Even under the BAU FS Gr Scenarios, the models do not predict an average growth of 13% per year in installed capacity. Further, electricity use per capita under all scenarios in Sub-Saharan Africa is projected to stay below 1500 kWh/capita till the middle of the century (equivalent to the average use in North Africa today) (Figure 6c, d). With imposition of climate policies, larger electric capacity is added in REMIND and IPAC compared to the baseline scenarios with greater deployment of carbon-free solar and nuclear technologies, but the models project lower average electricity use. Whether more rapid electricity capacity growth results in higher connectivity for the entire population will rest ultimately on the effectiveness of policies that enhance equity in access to and use of electricity on the sub-continent, something the models are unable to capture as yet.

4.4 RESIDENTIAL ENERGY MIX

Households in developing regions employ a range of fuels and technologies to meet their energy demands. However, among poor households, reliance on solid fuels (e.g. traditional biomass), self-collected and burnt in inefficient devices is extremely high (Pachauri et al. 2012). With growing affluence and urbanization, a transition to using more efficient liquid, gaseous and grid carriers has been observed in other nations (Pachauri and Jiang 2008). Such a transition has positive developmental benefits as it reduces drudgery and health impacts for households associated with solid fuel use.

Only one of the models participating in the RoSE project includes a breakdown of residential sector final energy use by type of energy. According to the GCAM projections, a clear transition away from traditional biomass use towards more efficient liquid, gaseous and grid sources of energy results in a decline in per capita final energy use between 2005 and 2030 (Figure 4 in SM). While not much variation in the total final residential energy use per capita is observed across the three medium population scenarios, there is a faster increase in the use of more convenient grid sources under the BAU FS Gr Scenario. Under the BAU HI Pop Scenario, the total final residential energy use per capita in 2050 is lower and the share of traditional biomass is significantly higher as compared to that in the other scenarios. Further, under climate policy, the transition away from traditional biomass is much slower.

As most of residential energy use in the region is used for cooking or lighting, applying some simplifying assumptions, allows us to estimate the likely continued reliance on traditional solid fuels for cooking. Assuming that no electricity and only half of liquid fuels are used for thermal purposes, and applying standard efficiencies of conversion in end-use devices (Ekholm et al. 2010), we project that in 2050, under the SL Gr, DEF and FS Gr Scenarios, about 30% of total cooking energy needs may still be met from solid fuels, whereas under the BAU HI Pop Scenario, about half of cooking energy needs may still be met using solid fuels. Under the climate scenarios, this share is projected to remain closer to two-thirds in 2030. This continued reliance on solid fuels for cooking in the region will have associated with it adverse health and welfare costs for its population unless widespread dissemination and use of advanced biomass cookstoves, that have performance characteristics similar to gas stoves, is encouraged.

5. CONCLUSIONS

This paper uses the RoSE population and economic growth pathways for the twenty-first century to characterize the potential future energy and emissions development for Continental Africa and for Sub-Saharan Africa. Population and economic growth rates influence the scale of African's economy, and its future energy use and emissions. However, our analysis shows that affluence levels are only one face of the medal, and the range of future emissions is only partly explained by the different economic trends. We show that technological factors could also be important.

In a medium economic and population growth scenario (BAU DEF), the share of global CO_2 emission of Continental Africa is approximately 20% in 2100 in both GCAM and IPAC. The range for Sub-Saharan Africa is between 4.0% and 9.8%. This variation indicates that African growth can be fueled by very different energy mixes and economic structures. A common finding across models is that in the absence of climate policy, the demand for fossil energy increases over time with economic growth to meet the growing energy needs and to replace the use of traditional bioenergy. Instead, should the growth of average per capita income remain low (as in the BAU HI Pop case), a large fraction of the population could continue to rely on traditional biomass. Regarding what the scenarios might imply for achieving some development-related energy goals, our analysis suggests that the share of electricity in final energy, electric capacity, and electricity use per capita all rise, while the traditional biomass share declines with growing affluence. Yet, the average levels of final energy and electricity use projected by the models across the different scenarios, even under fast economic growth (BAU FS Gr), could fail to ensure a minimum threshold use for everyone. Climate policy could result in more rapid electric capacity growth if carbon-free sources become competitive, but lower average electricity use in the short-run. The models cannot really inform us of whether the higher electricity capacity enables greater access for the entire population. Despite the fundamental role of economic growth in increasing energy access and some potential co-benefits with climate policy, it is likely that dedicated policies that enhance equity across the region will be needed.

The analysis carried out here makes an important contribution to the scenarios literature by focusing on a region that has been rather underexplored to date. Since Africa starts from a low base, both in terms of per capita income and per capita energy use, its potential future development is uncertain. Which development pathway Africa follows will influence its emissions and could potentially impact global emissions due to the projected size of Africa's economy and population. At the same time, this analysis raises issues for further research and investigation. A more explicit incorporation of efficiencies of end-use technologies in future analysis and model development would strengthen links between macroeconomic growth trends and energy service demands, which are what ultimately link to development. In addition, further comparative analysis across regions, would allow for a better understanding of the drivers of energy demand in the region and for assessing similarities and differences in patterns of change from other developing regions. Furthermore, this research does not address institutional and financial issues, and such additions could be explored in future work. Finally, a more refined analysis of the development and welfare impacts of differing socio-economic and energy futures in the region will require future model-based scenario analysis to incorporate greater heterogeneity and disaggregation that captures differences across population sub-groups and end-use sub-sectors.

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28

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