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Long-term development perspectives of Sub-Saharan Africa under climate policies

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Abstract

Ambitious climate policy increases the cost of energy and therefore has important interactions with the prospects of development in the countries of Sub-Saharan Africa. These interactions include the potential for gain for the continent in the form of new trade opportunities and climate finance. In this paper we quantify the costs and benefits of climate policy in Sub-Saharan Africa. Using an Integrated Assessment Model, we consider key characteristics of the continent, including the favorable conditions for renewable energy. A newly designed scenario analysis allows identifying the main drivers of the results. We show that Sub-Saharan Africa could implement climate policy in line with the 2°C target at roughly net zero costs if the international community follows up on its commitment towards supporting developing countries as declared in the Paris Agreement. Sub-Saharan Africa could become an important supplier of energy from biomass and could thus even benefit from more ambitious climate policy due to higher demand for this source of energy. The absence of a painful trade-off between short-term development and long-term climate stabilization could provide policy-makers with a much richer policy option space than previously considered. One such option is to link climate policy with poverty reduction through, for example, the provision of clean electricity.

Keywords: climate policy, development, climate finance, energy system transformation, mitigation costs

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1 Introduction

Does climate policy slow economic growth of countries in Sub-Saharan Africa? The answer to this question largely determines the incentives in this world region for participation in ambitious climate policy regimes. Turning away from proven development pathways based on fossil fuels requires costly additional investments into the energy system. Nevertheless, large renewable energy potentials, in particular for solar energy, and international technology diffusion could ease the transformation towards a low carbon economy and thus facilitate the adoption of emission reduction commitments. Additionally, countries in Sub-Saharan Africa could benefit from interactions with other world regions in the form of climate finance, international technology policies, and exports of bioenergy. While Sub-Saharan Africa consists of very heterogeneous countries, we consider a focus on the region as a whole a useful starting point for understanding the implications of an ambitious global climate policy regime.

In this paper we provide an aggregate and quantitative assessment of ambitious climate change mitigation on economic development in Sub-Saharan Africa. This assessment includes costs, in particular for the low-carbon transformation of the energy system, and benefits like climate finance and bioenergy trade. We take the renewable energy potential of Sub-Saharan Africa, international fossil fuel markets, and technology diffusion from other world regions into account. We find costs and benefits of climate change mitigation to be on the same order of magnitude, allowing Sub-Saharan Africa to participate in global mitigation efforts at roughly net zero costs. Additional benefits of climate policy would result from avoided climate impacts, which are not even taken into account in this study. Economic output is certainly not the only concern for decision makers in Sub-Saharan Africa, but a comparatively strong economy will help governments to face other challenges as formulated in the Sustainable Development Goals for example.

As a first contribution, we spell out the costs and benefits that are largely determined by the degree of international cooperation: countries in Sub-Saharan Africa benefit from rising demand for biomass on international markets under climate policies and from international burden sharing agreements based on equal emissions allowances per capita. Second, while a limited degree of international cooperation on climate and technology policies raises the costs of reaching climate targets globally, countries in Sub-Saharan Africa may by contrast experience lower costs, though associated with increased inequality in the intergenerational distribution. Third, potentially very regressive effects due to rising fuel prices highlight the need for careful climate policy implementation and complementary policies within countries.

Cost-effectiveness analyses using Integrated Assessment Models (IAM) indicate that climate stabilization goals can be achieved at moderate GDP losses in global aggregate (Kriegler et al., 2014). Some of these studies spell out the regional losses and gains underlying the aggregate global losses (Tavoni et al., 2015, Aboumahboub et al., 2014; Luderer et al., 2012). Only very few studies give detailed consideration to individual regions. Calvin et al. (2016) and Lucas et al. (2015) analyze the effect of economic growth on future global energy demand and emissions under different baseline and climate policy assumptions for Sub-Saharan Africa. This paper presents the first IAM-based study with a particular focus on Sub-

Saharan Africa. It quantifies the feedback of climate policy on economic growth in a set of scenarios and provides a breakdown into the different contributing factors.

In previous studies, four categories have been identified as major drivers of the net effect of climate change mitigation on development in Sub-Saharan Africa. First, if principles of global equity are considered (as the Paris Agreement has indicated that they will), countries in Sub-Saharan Africa can expect to benefit from financial transfers, for example in the form of climate finance (Jakob et al., 2015). Second, African countries can draw on low-carbon technologies developed by technology leaders (Collier et al., 2008). Third, many countries in Sub-Saharan Africa are well positioned to decarbonize their energy systems due to large endowments of hydro and solar power potentials (Collier and Venables, 2012; Pietzcker et al., 2014). Fourth, Sub-Saharan Africa has a large potential for producing biomass (Dasappa, 2011) that could be used domestically or sold on international markets. This paper quantifies the net cost of mitigation for Sub-Saharan Africa using REMIND, an IAM with high detail in the energy sector (Leimbach et al., 2010). While the four mentioned mechanisms affect a number of African countries we are aware that due to the heterogeneity of countries (e.g. differences in endowments with hydro power and biomass resources) our results will not hold for all of them.

Historically, development has been based on the use of fossil fuels (Smil, 2000; Fouquet, 2010; Jakob et al., 2012). How low-income countries can “leapfrog” an energy and emission intensive development phase and reach levels of high income with clean forms of energy use has been discussed intensively (Ward and Shively, 2012; Steckel et al., 2013). Marcotullio and Schulz (2007) find that developing countries today are using energy in a cleaner and more efficient way than their earlier predecessors. Concerning Africa in particular, Sokona et al. (2012) find that “Africa has the benefit of diverse experiences and models, both successful and failed ones, to assist it in fast-tracking energy pathways”. We follow this literature in the general idea that development patterns can change over time and explore how Africa can take advantage of its unique situation.

The paper is structured as follows. In Section 2 we give a brief description of the model and the scenarios that are explored in the following sections. Scenarios are designed along the dimensions of ecological efficiency, international cooperation on climate and technology policy, and equity in international agreements. The discussion in Section 3 focuses on the comparison of economic costs Sub-Saharan Africa as a model region is confronted with in the different scenarios. The analysis also addresses distributional impacts of different burden sharing schemes. Section 4 explores the requirements of the energy system transformation, including an ex-post analysis of distributional effects of this transformation within the region. We end with conclusions in Section 5.

2 Model description and scenario implementation

2.1 REMIND

REMIND is a global, multi-regional, energy-economy-climate model (Leimbach et al., 2010) used in long-term analyses of climate change mitigation (e.g. Bauer et al. 2012, Bertram et al., 2015). A detailed model description is provided by Luderer et al. (2015). The remainder of this section briefly introduces the model.

The world is divided into eleven model regions, one of which is Sub-Saharan Africa. This region contains all countries on the African continent except Algeria, Egypt, Libya, Morocco (incl. Western Sahara), South Africa, and Tunisia. It would be desirable to have resolution on a country level, but as climate change analysis requires a global model, the regional resolution is constrained by computational limitations (i.e. limitations of solving large-scale numerical models). We consequently focus on Sub-Saharan Africa as a single model region interacting with other regions in a global model.

The macro-economic core of REMIND is a Ramsey-type optimal growth model in which intertemporal global welfare is maximized. The model computes a unique Pareto-optimal solution that corresponds to the market equilibrium in the absence of non-internalized externalities. Model regions trade final goods, primary energy carriers, and in the case of climate policy, emissions permits. Macro-economic production factors are capital, labor, and final energy.

Economic activity results in demand for different types of final energy (electricity, solids, liquids, gases, etc.), determined by a production function with constant elasticity of substitution, and differentiated by stationary and transport uses. The energy system accounts for regional exhaustible primary energy resources through extraction cost curves. Bioenergy comes from different feedstocks: traditional biomass and first generation biomass, both assumed to phase out in the near future, as well as lingo-cellulosic residues and purpose-grown second-generation biomass. The regional biomass potential is represented by regional supply curves[1]. Accordingly, Sub-Saharan Africa has the second highest biomass potential – around 25% of the global potential (Klein et al., 2014, Fig.1). Global biomass supply is limited to at most 300 EJ per year in our model, motivated by biophysical limits (Smith et al., 2015), concern for food security (Popp et al., 2011), and potential negative side effects of large-scale biomass production (Creutzig et al., 2015). Non-biomass renewable energy potentials are reflected in detail on the regional level: Sub-Saharan Africa, for example, has an annual potential of solar energy for photovoltaic production of 200EJ with high capacity factors (Luderer et al., 2015, Fig. 5). Future solar power deployment depends on its costs, which for solar photovoltaics have recently been declining steeply (Walwyn et al., 2015; IRENA, 2016). In REMIND, investment costs for photovoltaics and concentrated solar power fall exponentially with their cumulative capacity, approaching floor costs. The modeling of

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[1] Biomass supply curves in REMIND are derived from the land use model MAgPIE (Lotze-Campen et al., 2008; Klein et al., 2014). Costs of biomass production hence include opportunity costs of some alternative land uses, e.g. using land for food production.

solar power, including assumptions on storage technologies and sensitivities to cost assumptions, is described in detail in Pietzcker et al. (2014).

More than 50 technologies are available for the conversion of primary energy into secondary energy carriers as well as for the distribution of secondary energy carriers into final energy. Techno-economic parameters (investment costs, operation and maintenance costs, fuel costs, conversion efficiency etc.) characterize each conversion technology.

The model accounts for CO_2 emissions from fossil fuel combustion and land use as well as emissions of other greenhouse gases (GHGs). A reduced form climate model is used to translate emissions into changes of atmospheric GHG concentrations, radiative forcing, and global mean temperature. It comprises an impulse-response function with three time scales for the carbon cycle, an energy balance temperature model with a fast mixed layer, and a slow deep ocean temperature box. Its key parameters are calibrated to reproduce MAGICC (Meinshausen et al., 2011), with a climate sensitivity of around 3.0°C.

The baseline scenario in REMIND is calibrated to the GDP trajectory of the SSP2 scenario of the Shared Socioeconomic Pathways (Dellink et al., 2017). Changes of GDP under climate policies are computed endogenously. Population and labor force input is derived from the SSP2 population scenario (KC and Lutz, 2017). Under these assumptions, the global economy grows throughout the 21^{st} century, while global population growth comes to a halt: Fig. 1 shows global GDP and population developments and the rising share of Sub-Saharan Africa in both – which increases from 1% to 13% for GDP, and from 10% to 25% for population.

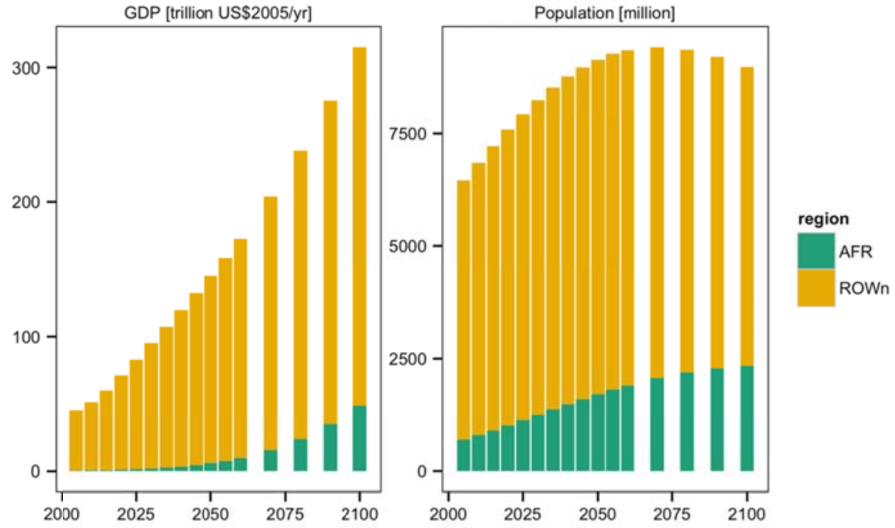

Fig.1: Global GDP and population scenario assumptions for the 21^{st} century in REMIND. The regions Sub-Saharan Africa (AFR) and Rest of the World (ROWn) are differentiated by color.

2.2 Scenario design and implementation

We introduce in this section a set of climate policy scenarios that are differentiated along three dimensions, all of which are expected to have a significant development impact:

(1) Ecological efficiency: Level of climate stabilization (i.e. global climate target)

(2) Cooperation: Degree of international cooperation regarding technology and climate policy

(3) Equity: Climate finance and burden sharing.

All scenarios are summarized in Table 1, and their differentiation along the three dimensions is described in the remainder of this section.

Table 1: Scenario matrix

Climate target	**Cooperation**		**Climate finance and burden sharing**		
			No climate finance	**Population share**	**Per capita convergence**
Baseline		BAU			
450 ppm	**full cooperation**		450TAX	450POP	450CC
550 ppm			550TAX	550POP	550CC
450 ppm	**Limited cooperation**		450SPA		
550 ppm			550SPA		

The first dimension reflects varying levels of ambition in global climate policy: Apart from a baseline scenario with no climate policy, there are two scenario sets that stabilize atmospheric greenhouse gas concentration at around 450 ppm CO_2 equivalent (CO_2eq)[2] and 550 ppm CO_2eq in the year 2100. The 450 ppm scenarios have a high probability of limiting the rise in global mean temperature in line with the 2°C target (Clarke et al., 2014). The benefits from avoided climate impacts are not included in our

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[2] The actual implemented targets are radiative forcing targets of 2.6 W/m^2 (corresponding to 450 ppm CO_2eq) and 3.7 W/m^2 (corresponding to 550 ppm CO_2eq), respectively. An intermediate overshoot in radiative forcing during the 21st century is allowed for the 450ppm scenario.

model. The 550 ppm scenario would cause warming beyond the 2°C target agreed in the Paris Agreement. Considering such a "weak climate policy" scenario, however, helps illustrating challenges of *stringent* climate policy in particular. An example is Africa's export of biomass, which plays a major role only in the 450 ppm scenario, see Section 3.2.

The second dimension takes into account that the international community may show limited or full cooperation with respect to climate change mitigation and technology policy. Climate policy may be enacted immediately under full cooperation to achieve the long-term climate target. The climate target is then enforced by either a globally uniform carbon tax or an emissions trading regime. By contrast, in the scenarios with limited cooperation (named 450SPA and 550SPA)[3], comprehensive climate policy only starts in the year 2040, but still reaches the same climate stabilization targets as in the cooperative scenarios. Until the year 2040, climate policies are assumed to be fragmented with regionally differentiated carbon prices. Sub-Saharan Africa starts at very low carbon prices of only 1 US$/t$CO_2$ in 2020 - compared to e.g. 12 US$/t$CO_2$ in USA or 5 US$/t$CO_2$ in China. Regional carbon prices converge towards a current price level of 100 US$/t$CO_2$ and 21 US$/t$CO_2$ in 2040 in the 450SPA and the 550SPA scenario, respectively, and further increase exponentially towards 1876 US$/t$CO_2$ and 386 US$/t$CO_2$, respectively, in 2100. The long-term carbon tax levels are substantially lower in the full cooperative scenarios, in particular in the 450TAX scenario with a level of 75 US$/t$CO_2$ in 2040 and of 1395 US$/t$CO_2$ in 2100.

The assumption on technology cooperation reflects whether international technology diffusion is actively supported or not. Emerging low-carbon technologies such as solar energy, wind power, and electric- and hydrogen-vehicles are subject to endogenous global technological learning in the REMIND model. Investments into these technologies cause spillover effects between model regions, as the costs for learning technologies decrease irrespective of where the capacity addition is made. In the scenarios with full cooperation, these spillovers are assumed to be fully internalized – for example by international agreements on technology policy – and the diffusion of low-carbon technologies is consequently accelerated. In the scenarios with limited cooperation, by contrast, spillovers are not internalized. This represents a world without cooperative technology policy. Technically, full and limited cooperation on technology are modeled by using two different solution algorithms, described in full detail in Leimbach et al. (2017).

The third scenario dimension reflects climate finance as part of international agreements on climate policy, and different underlying equity and fairness criteria. We consider three alternatives here: No climate finance at all or climate finance realized by two different burden sharing schemes in international climate agreements motivated by equity considerations.

In the scenarios with no climate finance at all (named "TAX" and "SPA"), regions enact carbon pricing in accordance with an international climate agreement starting in 2015 in scenarios with full cooperation,

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[3] SPA stands for shared policy assumption and characterizes a class of scenarios that assume a phase of fragmented, i.e. non-cooperative, climate policy.

and in 2040 under limited cooperation. There is neither an allocation of emission permits to regions, nor any other sort of financial transfer between model regions. Technically, we compute these scenarios using exponentially rising global carbon tax paths compatible with the respective global climate target[4] to arrive at a cost-efficient solution. In the absence of climate finance, developing regions would face rather high costs (Tavoni et al., 2015) which conflicts with the principle of common but differentiated responsibilities in the Paris agreement.

The two other climate finance scenarios assume an explicit burden sharing scheme as part of an international climate agreement in line with a global climate target. In these cases, climate finance is realized as the allocation of emission permits to regions in accordance to the burden sharing scheme. Once allocated, emission permits can be traded in our model, and generate revenues for permit exporting regions as a particular form of climate finance. Technically, we compute the cost-efficient solution by allocating a permit budget compatible with the global climate target to regions and making sure the permit market clears. We consider two different burden sharing scheme scenarios, motivated by equity considerations: per capita convergence (named “CC”) and population share (“POP”)[5]. In the prominently discussed CC scheme (Meyer, 2000), the global emission permits (determined by the globally optimal emission pathway) are allocated as a weighted average of each regions’ share in global emissions in 2005 and an equal per capita share. Weight of the latter increases linearly over time. As of 2050, permits are allocated to the different regions according to the equal per capita rule only.

The POP scheme, not yet used in integrated assessment studies so far, is based on a different rule of equal per capita allocation. The share S of region r in global permits is based on the cumulative population share over the 21st century ($t=1,\dots,T$):

$$S_r = \frac{\sum_t P_{r,t}}{\sum_t \sum_r P_{r,t}}$$

Population values $P_{r,t}$ are determined by the SSP2 population scenario described above.

Comparing the two allocation schemes, the POP scheme is more favorable towards developing countries than the CC scheme (and may thus be considered more equitable), especially in ambitious mitigation scenarios, for two reasons: First, In the early century global emissions are still quite high, and hence the global permit budget allocated in each period is large. In the CC scheme, countries with a high initial emission share receive most of these permits. In the POP scheme, by contrast, countries with large populations, in particular those countries with additional high population growth, benefit from the allocation. Second, global emissions have to decline in the second half of the century and can even become negative. Under the CC burden sharing scheme, countries with high population and high population growth, that already get a comparatively low amount of permits in early periods, do not

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[4] Convergence towards the climate target is achieved by iteratively adjusting the initial tax according to the reaction of the climate system.

[5] A recent survey of burden sharing schemes is found in Zhou and Wang (2016).

benefit from the equal per capita permit allocation in the second half of the century since the remaining emission budget is low.

Countries in Sub-Saharan Africa, which are expected to have high population growth rates, would likely benefit from the POP burden sharing scheme.

3 Development Impacts of Mitigation Policies

In this section we discuss the development impacts of mitigation policies by evaluating the economic cost of mitigation for Sub-Saharan Africa, also in comparison to other regions. As a measure for the mitigation cost, we choose discounted aggregated consumption losses of a mitigation scenario compared to the respective baseline scenario as a percentage of the discounted aggregated baseline consumption. Aggregation and discounting is always over the time horizon from 2010 until 2100. We find that differences in mitigation costs between regions in general are at least as significant as differences between scenarios. Noting that scenario-independent variation of mitigation costs identifies structural differences of regions, we find that regions with a comparatively high income share of energy or with a high share on fossil fuel exports face higher mitigation costs than other regions.

3.1. Mitigation costs in scenarios with varying climate target and cooperation

Differences in mitigation costs are largest along the scenario dimension of ecological efficiency (see Fig. 2). Global mitigation costs amount to 0.4% of discounted consumption for the 550TAX scenario and around 1.5% for the 450TAX scenario. All regions demonstrate higher mitigation costs with a more ambitious climate target. Sub-Saharan Africa faces mitigation costs above global average that amount to 1.4% and 2.9% for the 550TAX and the 450TAX scenario, respectively.

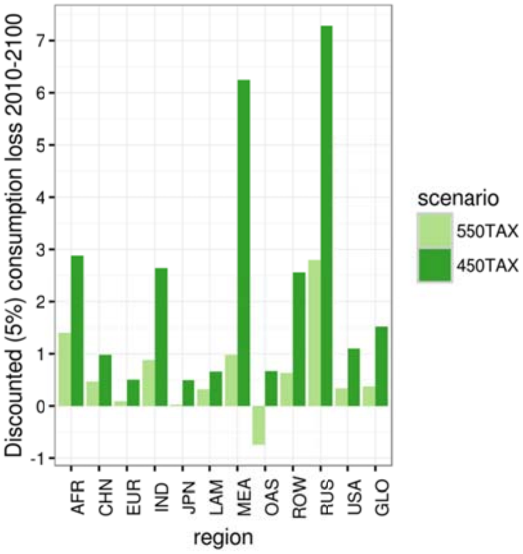

Fig. 2: Mitigation costs under scenarios with varying climate target (AFR - Sub-Saharan Africa, CHN - China, EUR - EU27, IND - India, JPN – Japan, LAM – Latin America, MEA – Middle east and North Africa, OAS – Other Asia, ROW- Rest of the World, RUS – Russia, USA – USA, GLO – World)

Limited cooperation between regions increases global mitigation costs. The combined effect of limited cooperation in technology and climate policy results in an increase of mitigation cost at the global level of around 0.04 and 0.2 percentage points for the 550 ppm scenario and the 450 ppm scenario, respectively (see Fig. 3). This is in line with other studies (e.g. Bertram et al., 2015). The isolated impact of cooperative technology policy is comparatively small since knowledge spillovers exist in our model independently of whether investors internalize this externality or not. Hence, the cost increase through limited technology cooperation is much smaller than the one through a delay in climate policy.

With delayed cooperation in climate policies, there is a lock-in effect that becomes more costly when technological cooperation is weak. For some regions though, limited cooperation results in lower mitigation costs. Mitigation costs in Sub-Saharan Africa decline by 0.15 percentage points in the 550 ppm scenario and 0.5 percentage points in the 450 ppm scenario. We identify two reasons for the lower costs: First, increasing demand for modern biomass on international markets. Scenarios with limited cooperation exhibit a very high carbon price in late periods to compensate for higher emissions earlier in the century compared to the cooperative case – this increases the demand for biomass, as it can be used in combination with carbon capture and storage (BECCS) to effectively create negative emission. Sub-Saharan Africa has significant potential for growing biomass, resulting in increasing exports in scenarios with limited cooperation. Second, the very low carbon price in Sub-Saharan Africa early in the century in scenarios with limited cooperation reduces the amount of costly emission reduction measures and thus lowers mitigation costs.

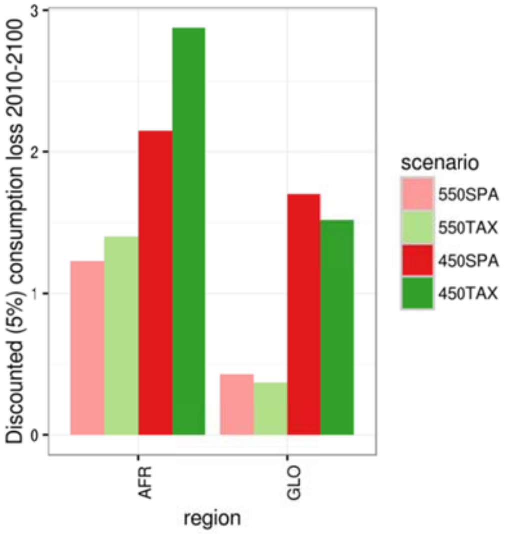

Fig. 3: Mitigation costs under scenarios with varying climate target and cooperation level (TAX – full cooperation, SPA – limited cooperation, AFR – Sub-Saharan Africa, GLO – World)

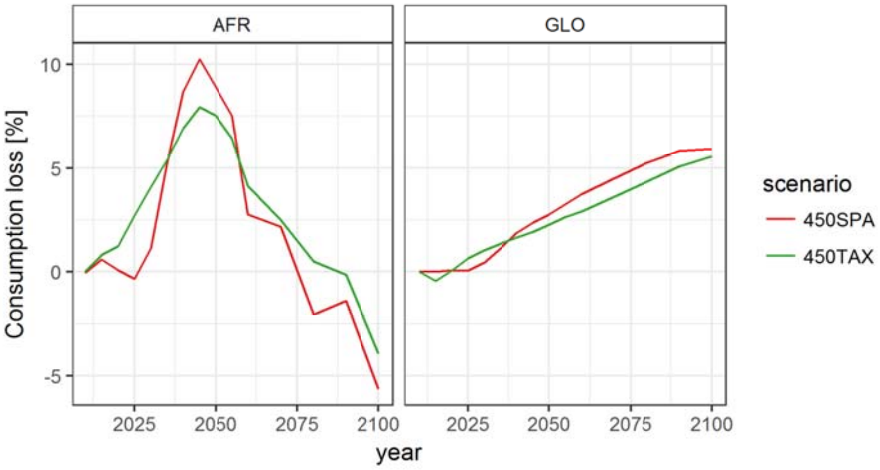

Fig. 4: Mitigation costs of Sub-Saharan Africa (AFR) and World (GLO) over time (mitigation costs are expressed as percentage reduction of baseline consumption in the 450SPA and 450TAX scenario)

While aggregated mitigation costs for Sub-Saharan Africa are slightly lower in the scenario with limited cooperation, the intertemporal distribution of mitigation costs is more extreme compared to the cooperative scenario and also compared to the global cost trajectory (Fig. 4). The generation living in Sub-Saharan Africa between 2040 and 2060 is exposed to the highest mitigation costs (between 3% and 10%), whereas the generations alive before 2030 and after 2075 bear no mitigation costs at all. While the cost profile in the cooperative scenario is similar, costs are less extremely distributed over time. This indicates that while immediate participation in a global climate policy agreement is in aggregate more expensive for Sub-Saharan Africa, it may attenuate intergenerational conflicts: a less extreme imbalance of costs and benefits of climate policy over time reduces the challenges associated with the distribution of net costs of climate policy across generations.

Regional mitigation costs have to be interpreted carefully. First, while for most regions mitigation costs are higher in the 450 ppm scenarios than in the 550 ppm scenarios, the more ambitious climate target implies more avoided climate change damages, which are not accounted for in our study. Second, in line with the majority of IAM mitigation studies in the literature, all climate policy scenarios considered so far assume an eventually uniform global tax to be implemented without any climate finance. While this ensures global efficiency, it disproportionately burdens less affluent countries. Burden sharing schemes that respect differences in historic responsibilities for emissions, as well as capacities to mitigate, change the distribution of mitigation costs, and are analyzed in detail in the next section.

The main reason to exclude climate damages from our assessment is the still rudimentary knowledge about their long-term consequences for societies and economies. Not accounting for damages means that the cost of climate mitigation are biased upwards, as benefits from avoided damages are disregarded. Hydropower for example is likely to be affected by reduced water availability, and much more so in scenarios without ambitious climate mitigation (Schaeffer et al., 2012, Adams et al., 2013; Schewe et al., 2014).

3.2. Mitigation costs in scenarios with varying permit allocation

This section discusses the implications for mitigation costs along the scenario dimension of climate finance and burden sharing. This dimension has no significant global effect, since efficiency and distribution are separable in our model – a common feature of many IAMs. By contrast, the effect on the regional distribution of income is very strong: We discuss the implications of different climate finance regimes as introduced in Section 2 for Sub-Saharan Africa. To avoid interference with the dimension of ecological efficiency in interpreting the results, we only compare scenarios with the same climate target.

Sub-Saharan Africa's mitigation costs are very strongly influenced by the climate finance dimension (Fig. 5). Compared to the scenarios without climate finance (450TAX, 550TAX), Sub-Saharan Africa has lower costs in the burden sharing scenarios. Under the per capita convergence scheme and the moderate climate target (550CC), climate finance has a large effect, and even results in negative mitigation costs of -0.5% for Sub-Saharan Africa (see Fig. 5). Under ambitious climate policy, however, the costs only decline moderately to 2.1% (450CC compared to 450TAX). The reason for this is that the time when Sub-Saharan Africa can take full advantage of the approached equal per capita allocation of emission permits coincides with the period where the annual global emission budget declines quickly to zero and even below. The second burden sharing scheme (450POP, 550POP), which is based on the cumulated population share, takes the underlying equity principle much better into account and reconciles the potentially opposite dynamics of the emission reduction paths and the demographic trajectory.

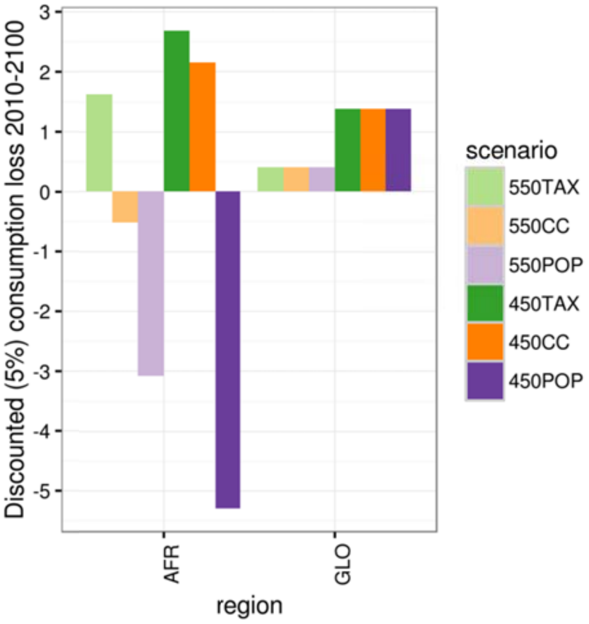

Fig. 5: Mitigation costs under scenarios with varying allocation rules (TAX – no climate finance, CC – per capita convergence, POP – cumulated population share, AFR – Sub-Saharan Africa, GLO – World)

Burden sharing according to population share (450POP, 550POP) results in much larger cost reductions for Sub-Saharan Africa than in the CC scheme (Fig. 5). Net costs in the case without climate finance (450TAX, 550TAX) turn into net benefits of mitigation: almost -5.3% of discounted consumption in the 450 ppm scenario and -3.1% in the 550 ppm scenario. For all other regions in aggregate, this implies an increase of mitigation costs in 450POP and 550POP scenarios, respectively, compared to 450TAX and 550TAX scenarios, respectively, in the order of 0.2 percentage points.

In order to explain why mitigation costs for Sub-Saharan Africa are lower for the more stringent climate target in the 450POP scenario as compared to the 550POP scenario, we decompose the mitigation costs into their drivers (Fig. 6) according to the methodology described in Aboumahboub et al. (2014). In the 450POP scenario, a GDP loss of around 5% and higher energy system costs of around 4% are overcompensated by savings on investments (1%) and fossil imports (3%), combined with additional income from biomass export (3%) and emission permit export (7%). The permit export generates revenues in particular in the first half of the century (e.g. around 340 billion US$2005 in 2030). The mitigation cost structure in the 550POP scenario is qualitatively similar to the one in the 450POP scenario. However, compared to the 550POP scenario, the 450POP scenario exhibits benefits from additional biomass and permit exports that exceed higher GDP losses and energy system expenditures. In effect, this leads to lower net mitigation costs for Sub-Saharan Africa under the more stringent climate target. The prospect of lower costs and net gains, respectively, may present an incentive for countries in Sub-Saharan Africa to support more stringent climate targets in international negotiations.

The amount of revenues from permit and biomass trading implies huge financial transfers. Jakob et al. (2015) point out that large climate transfers might cause problems if administered poorly. Such a "climate finance curse" could be caused by high volatility of transfers due to large price changes for emission permits, a "Dutch disease" effect, and increased rent-seeking and corruption. These adverse effects could potentially be avoided through a number of measures including improved (financial) institutions, or international involvement through the Green Climate Fund. Financial transfers thus have a great potential to render a climate agreement equitable, but they must be administered with care.

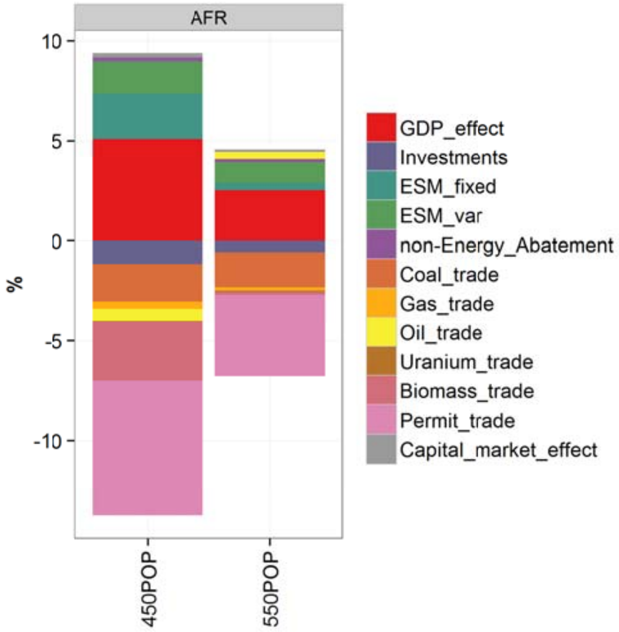

Fig. 6: Decomposition of mitigation costs (contribution of different factors to consumption losses in policy scenarios - 450POP and 550POP - compared to baseline scenario; negative values represent consumption gains)

4 Transformation of the energy system

Mitigation costs as discussed in the last section arise from a transformation of the energy system away from fossil fuels towards low carbon energy supply. The drastic reductions in global GHG emissions necessary to meet ambitious climate targets are shown in Fig. 7. The climate target determines the global emission trajectory to a large extent and hence the necessary mitigation efforts. In the baseline scenario, fossil fuel consumption increases greenhouse gas emissions to up to 87 $GtCO_2eq$ in 2080. By contrast, to reach low climate stabilization targets, emissions must decline almost immediately from today's level in the 450TAX scenario, or stabilize at around 55 $GtCO_2eq$ before declining in 2040 in the

550TAX scenario. In the long run, emissions are even negative (CO_2 removal from the atmosphere with technologies such as BECCS) in the 450TAX scenario, or close to zero in the 550TAX scenario.

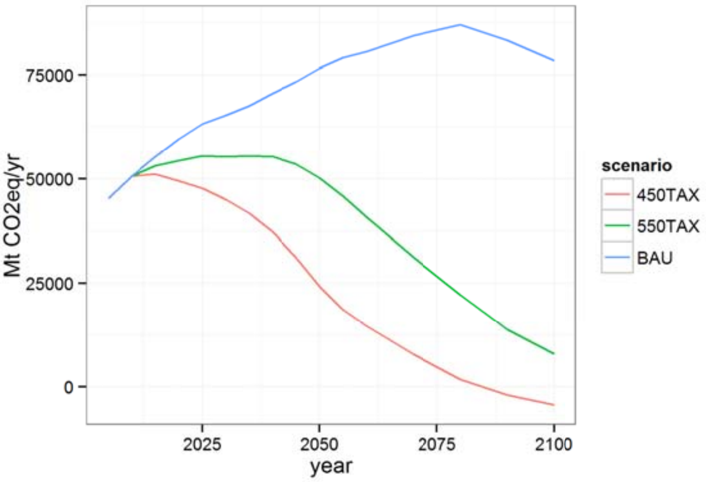

Fig. 7: Global GHG emissions in Mt CO_2 equivalent

4.1 Transformation under full cooperation

In this section, we discuss the challenges of the low carbon transformation of the energy system in Sub-Saharan Africa in the case of fully cooperative scenarios. As the equity dimension has no impact on this transformation, we focus on comparing BAU and TAX scenarios.

Sub-Saharan Africa has the highest growth rate in energy demand across model regions during the 21st century (Fig. 8), as acceleration of economic growth in early development stages is often very energy intensive. Under climate policy, countries in Sub-Saharan Africa face two mayor challenges regarding their energy system transformations: First, the growth in energy consumption has to be reduced from baseline levels. The 450TAX (Fig. 8) and 550TAX scenarios show around 20% less final energy consumption in 2050 and beyond, implying large efforts in increasing energy efficiency.

Second, while in the baseline scenario the use of final energy shifts slowly from solids (first traditional biomass, later coal) towards a balanced mix of liquids, gases, and electricity, the increase in the electricity share is much faster in climate policy scenarios. In the 450TAX scenario the electricity share is above 30% in 2050 and above 70% in 2100 - much higher than the share of 40% in 2100 in the baseline scenario. The higher electricity share goes along with a growth rate of installed power generation capacities by 10% per year over the next two decades, which is close to the 13% that Bazalian et al. (2012) mention as what is required to provide universal electricity access in Sub-Saharan Africa. Sub-Sharan Africa catches up with other regions. While the ratio between the per capita electricity consumption in Sub-Saharan Africa and ROW is still 1:18 in 2010 it is only 1:3 in 2050.

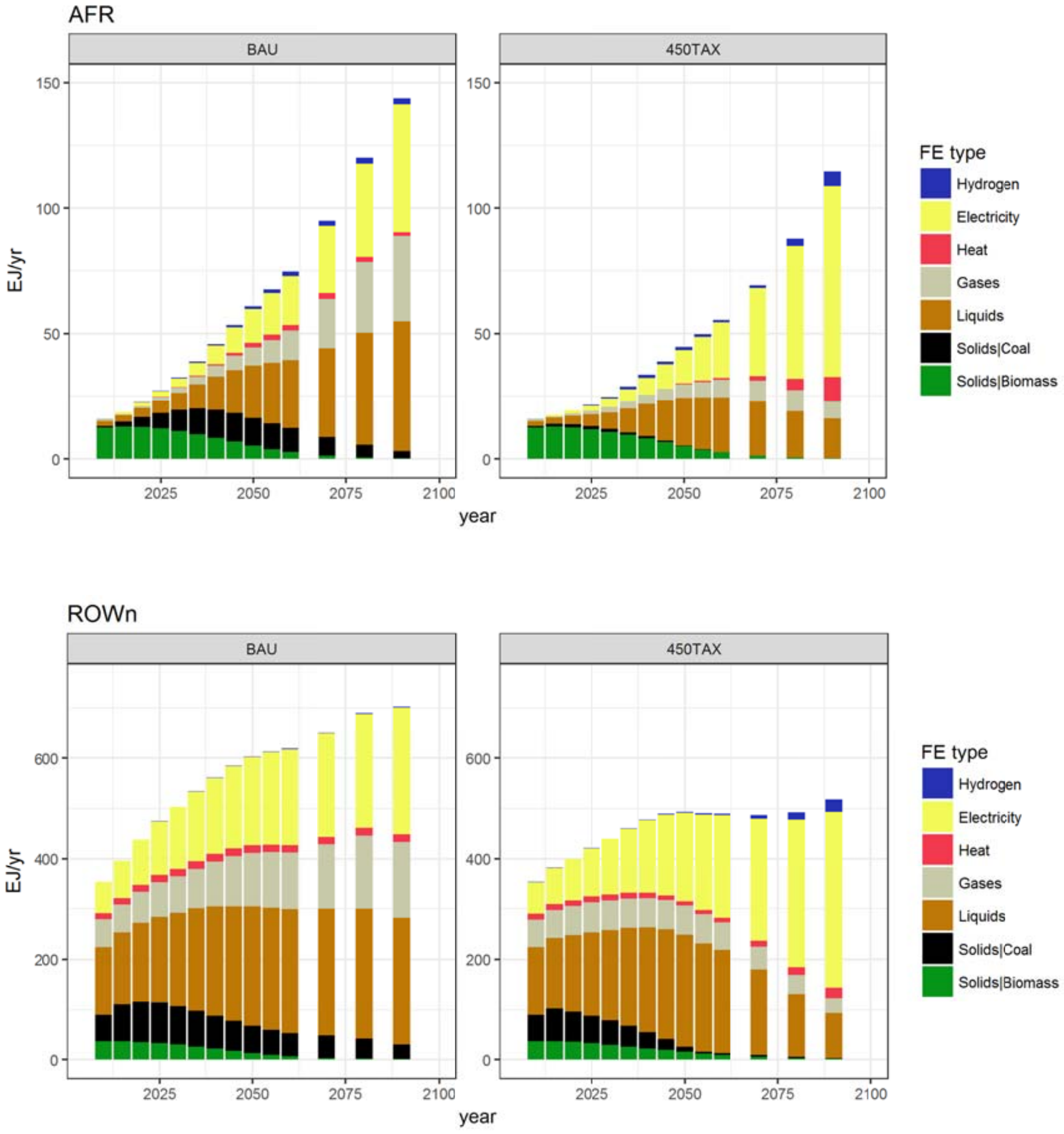

Fig. 8: Final energy consumption in baseline and climate policy scenario; upper panel: Sub-Saharan Africa (AFR); lower panel: all other regions (ROWn)

Despite increasing energy demand, final energy intensity is decreasing over time in all regions under climate policy (Fig. 9): In the 450TAX scenario, the global average declines from 7.3 MJ/US$2005 to 2.3 MJ/US$2005. Sub-Saharan Africa converges towards the global average in 2100 starting from a final energy intensity of more than 30 MJ/US$2005 in 2005. Convergence of regional final energy intensity is weaker in relative terms: The ratio between the highest and lowest regional intensity decreases from around 10 to 5 between 2005 and 2100.

Final energy per capita also converges slowly across regions (Fig. 9). Countries in Sub-Saharan Africa increase their per capita demand significantly, while demand is still lower than in developed regions, which either keep their current levels or as for the USA reduce them substantially.

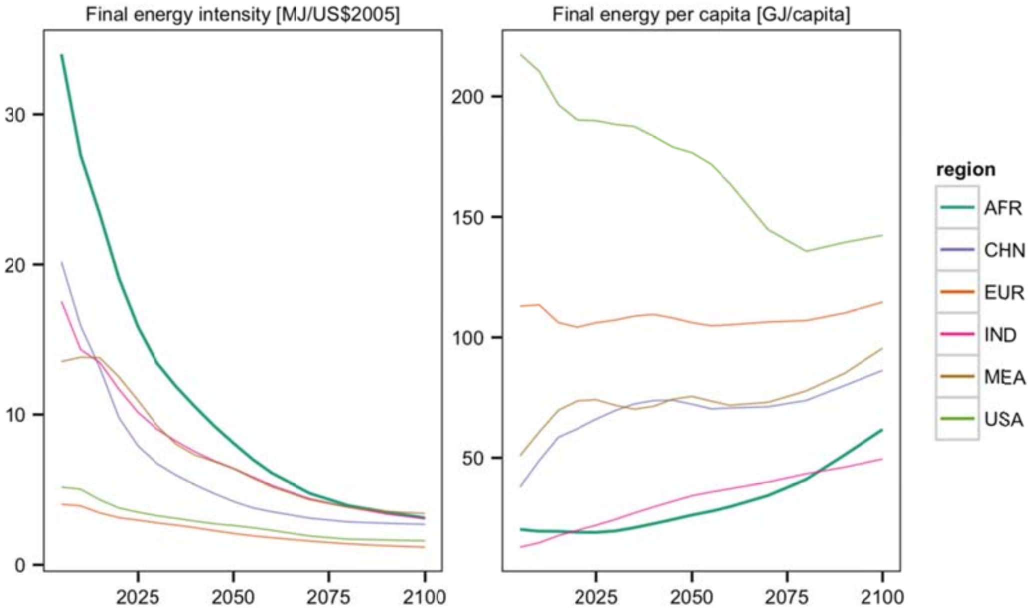

Fig. 9: Final energy intensity (left) and final energy demand per capita (right) in 450TAX scenario; the thick line represents Sub-Saharan Africa

Climate policy implies a major shift from the use of conventional energy conversion technologies (e.g. coal-fired power plants) to modern and more capital intensive renewable energy technologies (e.g. solar and wind). The higher capital intensity means that a higher share of the cost needs to be financed upfront (Hirth and Steckel, 2016). While the primary energy mix in both policy scenarios already shows some divergence from the baseline energy mix in 2050, it is completely different by the year 2100 (Fig. 10). In the short term, the use of coal is nearly completely phased out in the policy scenarios. In the 450TAX scenario, gas consumption is reduced significantly and combined with CCS technologies in the production of electricity. Oil is used throughout the century (to a smaller extent in the 450TAX scenario than in the 550TAX scenario) since a full decarbonization of the transport sector is more costly than mitigation options in other end-use sectors.

Differences in the energy mixes between the 450TAX and 550TAX scenarios indicate different mitigation strategies. Up to 20% less primary energy consumption (e.g. in 2030 and 2070 – see Fig. 10) in the 450TAX scenario compared to the 550TAX scenario results to a certain extent from additional energy efficiency improvements in scenarios with more ambitious climate targets. CCS as well becomes much more relevant in these scenarios, and is of particular relevance when used in combination with biomass, as this generates negative emissions.

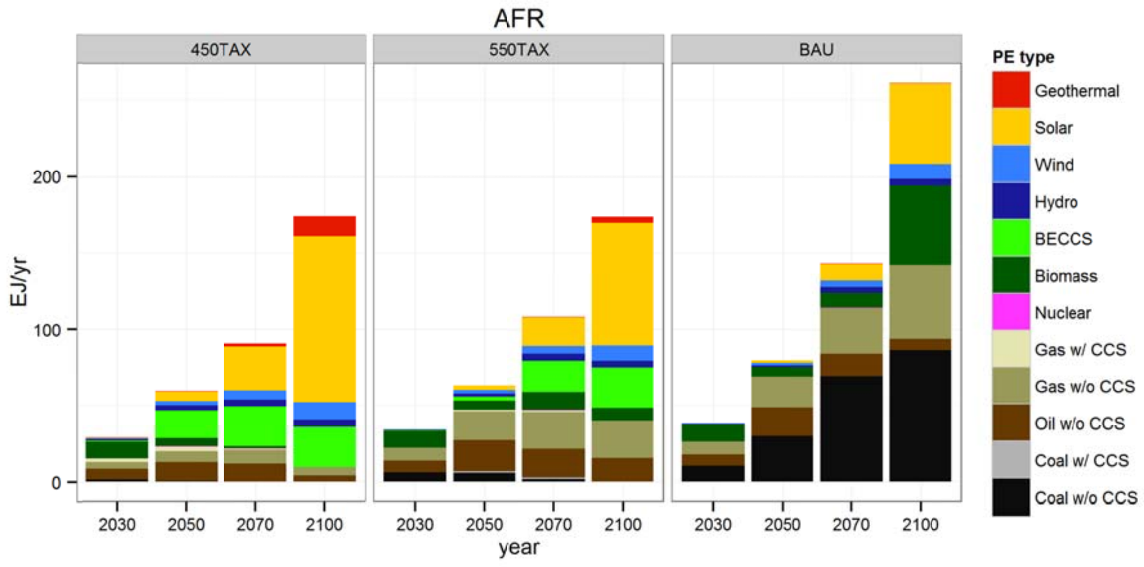

Fig. 10: Consumption of primary energy carriers in Sub-Saharan Africa at selected years for 450TAX, 550TAX and BAU scenarios (BECCS – biomass use with carbon capture technologies, CCS – carbon capture technologies)

The optimal primary energy consumption path of the model region Sub-Saharan Africa under ambitious climate policy can be summarized as follows. Until 2050, production of biomass is scaled up drastically. Part of this is used abroad. In a number of regions domestic biomass production falls short of demand, thus giving Sub-Saharan Africa the opportunity to export biomass. From mid-century on massive investments into renewable energies, predominantly solar energy, follow. This scenario thus hinges on the availability of technologies for modern biomass in the medium term and solar energy in the long term. Making use of the biomass and solar energy potential in countries of Sub-Saharan Africa has major institutional, financial, and labor requirements. Large-scale biomass deployment could also cause environmental and socioeconomic damages, for example on biodiversity, land and water supply, employment, or social assets (Creutzig et al., 2015).

Ambitious climate polices require significant increases in energy system investments. As shown in Fig. 11, energy system investments in 2100 in the 450TAX scenario exceed the baseline investments by more than 30% in Sub-Saharan Africa. This implies an increase of the energy investment share in GDP from 6%

today to 10% over the next three decades. By contrast, the average share across other regions is below 5% today and declining. Around one third of Sub-Saharan Africa's energy investments in the second half of the century are into solar power.

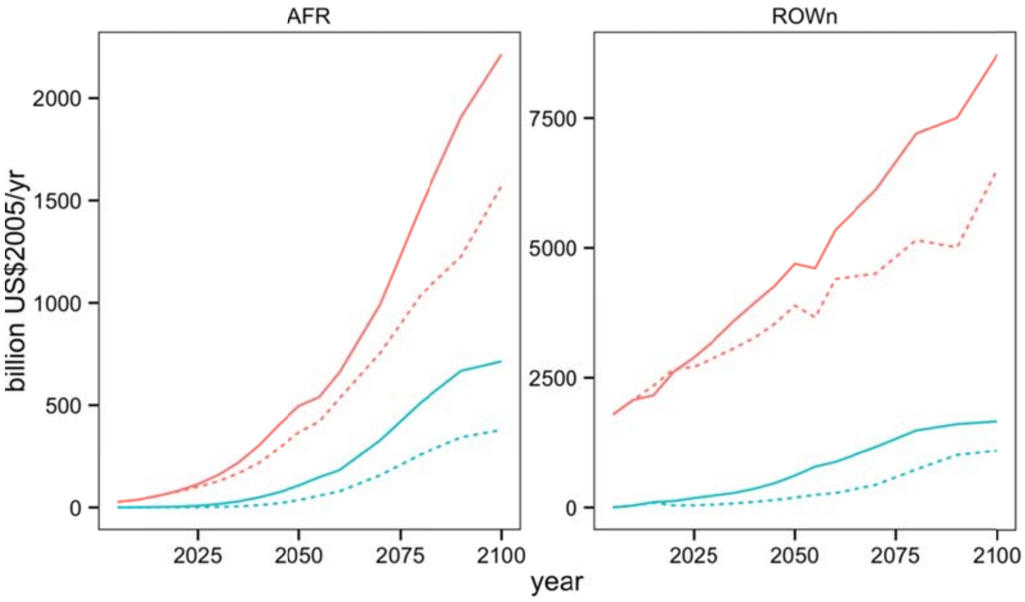

Fig. 11: Energy system investments of Sub-Sharan Africa (AFR) and Rest of the World (ROWn) in baseline scenario (dotted lines) and 450TAX scenario (solid lines); Total energy investments in red; investments in solar technologies in blue (note the different scaling of the y-axes).

4.2. Transformation under limited cooperation

Scenarios that differ in their level of cooperation show different global mitigation strategies, though the impact is less significant than for the variation of the climate target. In scenarios with limited cooperation, carbon pricing is very low early in the century in Sub-Saharan Africa and technology diffusion is not actively supported by global technology policies. As a result, the buildup of low-carbon technologies slows down compared to a scenario with full cooperation. For example, the share of solar power in the electricity mix of Sub-Saharan Africa in 2050 is only 25% in the scenario with limited cooperation (450SPA), while much higher at 42% in the cooperative scenario (450TAX).

Furthermore, limited cooperation implies more fossil use and slower reductions in primary energy consumption: The coal share in primary energy is still around 20% in 2030 in the 450SPA scenario, while less than 5% in the 450TAX scenario. Primary energy consumption is also significantly higher in the year

2030: 33 EJ in the non-cooperative and 29 EJ in the cooperative scenario. Limited cooperation requires higher mid-century emission reduction rates in Sub-Saharan Africa compared to the full cooperative scenario.

While limited cooperation on climate policy implies lower mitigation costs for Sub-Saharan Africa, one of the risks is a potential carbon lock-in: For countries in Sub-Saharan Africa, many of which have to build up large power generation capacities in the near term, the low carbon price in the early periods results in a carbon-intensive energy mix, compared to the scenarios with full cooperation. This so called carbon lock-in, as discussed in detail in Bertram et al. (2015), may be problematic for at least two reasons: First, if countries should depart from the limited cooperation scenario and enact more stringent climate policy earlier than originally intended, parts of the fossil fuel infrastructure would have to be retired before the end of their long economic life-times – the risk of stranded assets. Second, there may be path-dependencies associated with energy investments, energy infrastructure, or the political economy beyond the ones reflected in our model. If that were the case, countries in Sub-Saharan Africa would face difficulties during their low-carbon transformations later in the century and bear costs beyond those modeled here under limited cooperation.

4.3. Distributional effects of climate change mitigation within Sub-Saharan Africa

While REMIND is well suited to analyze distributional effects of climate change mitigation between regions, some limited conclusions can be drawn on the distributional effects within regions as well. A large share of the African population currently lives on incomes below the poverty line, and a substantial fraction of expenses in poor households is used for energy. Kaygusuz (2011) states that "The International Energy Agency (IEA) expects that the number of people depending on biomass for cooking will rise to around 2.7 billion in 2020, from 2.5 billion today". Most of these people will likely live in Africa. Hailu (2012) finds that in 2011 585 million Africans (30.5%) had no access to electricity. Rising overall energy prices could worsen poverty and increase inequality, since people without access to electricity have to acquire liquid and solid fuels that are likely subject to relatively higher price increases (see below). They would thus be disproportionally affected by rising energy prices (Jakob and Steckel, 2013).

Higher energy prices due to climate policy may thus reduce the remaining income of the poor even more and cause or worsen energy poverty for this large part of the population. This can be illustrated with a simple identity,

$$I - pE = C \qquad (1).$$

Here I is the income of a certain income group, E is subsistence-level final energy consumption as defined in Barnes et al. (2011) for example, p is the price for energy and C is remaining consumption (including energy consumption above subsistence level).

In order to determine the long run development of the remaining consumption we can represent income as

$$I = \varphi Y \qquad (2).$$

φ is the income share of a particular income group. In our case the bottom 10% for example are of particular interest. Y is total economic output. The growth rate of the remaining consumption is thus given by

$$\frac{\acute{C}}{C} = \acute{\varphi}\frac{Y}{C} + \acute{Y}\frac{\varphi}{C} - \acute{p}\frac{E}{C} - \acute{E}\frac{p}{C} \qquad (3).$$

It follows that this growth rate is positive if and only if

$$\frac{\acute{\varphi}}{\varphi} + \frac{\acute{Y}}{Y} > \left(\frac{\acute{p}}{p} + \frac{\acute{E}}{E}\right)\frac{pE}{C+pE} \qquad (4).$$

We can thus study the effect of climate change mitigation on non-energy consumption by considering the terms in this inequality.

The amount of subsistence-level energy consumption, E, is by and large constant over time. Barnes et al. (2011) point out that the minimum requirement may depend on culture, which determines cooking habits, and region, which determines heating requirements, but does not mention dependence on time. Krugmann and Goldemberg (1983) do not consider time variance either. We thus assume E to be time invariant.

The income share of the poorest households φ may change for two reasons. One reason is the natural evolution of inequality. Deininger and Squire (1996, Table 5) see the Gini coefficient in Africa fluctuating between 43 and 50 (on a scale from 0 to 100) between the 1960s and the 1990s. Alvaredo and Gasparini (2011) review several publications on inequality in Africa and find that it stayed quite stable in the 1990s and 2000s. We therefore assume that inequality within Africa is roughly stable over time. The second reason why the share of income for the poorest households may rise could be pro-poor redistribution by the government. In order to identify potential adverse consequences of climate policy, we assume that governments do not engage actively in reducing inequality and thus keep φ constant.

If E and φ are constant and C is small, inequality (4) shows that the sign of the growth rate of consumption for goods other than minimum energy requirements depends strongly on the relative size of the growth rate in output Y and the energy price p. To be precise, the growth rate is only positive if the growth rate of output is larger than the product of the growth rate of the energy price and the share of energy expenditures in total income $pE/(pE + C)$. As a rule of thumb, the growth rate of consumption is only positive if the growth rate of output is larger than the grow rate of the energy price. Fig. 12 shows the level of per capita income and final energy prices in REMIND compared to the base year 2010. The development of these variables in the business-as-usual scenario is contrasted with those in a scenario with ambitious climate policy. We chose the price for liquids as representative for energy from fossil fuels. The share of households in Sub-Saharan Africa using liquid fuels (kerosene and liquefied petroleum), although still low today, is significant and increasing. Its importance is emphasized by Pachauri et al. (2012). Climate policy sets up a carbon price and causes the price for liquid energy to rise much faster in the policy scenario (450TAX). While liquid fuels are to a significant share fossil-based even in the second half of the century, electricity generation has quickly been decarbonized, such that electricity prices grow slower than prices for liquid energy in all scenarios.

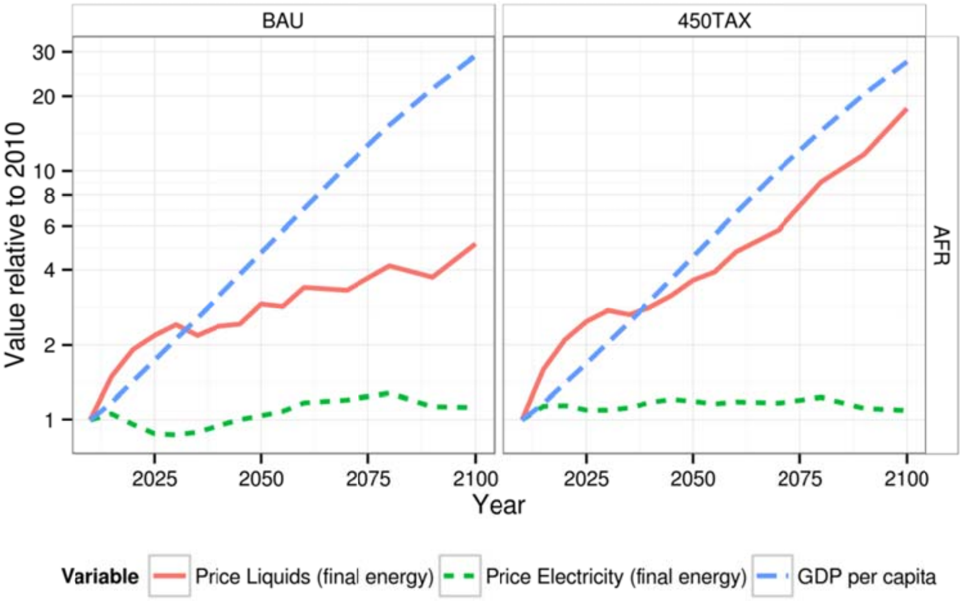

Fig.12: Growth paths in income per capita, prices for liquids, and the electricity price in the baseline and 450TAX scenario (variables are normalized to their values in 2010, and shown on a logarithmic scale)

The low rate of electrification in Africa cited above implies that the poorest households currently strongly rely on traditional biomass (solids) and fossil liquid fuels. If this dependence persists, our results indicate that they may see a declining share of non-energy consumption until 2030. Climate policy would in addition strongly reduce the scope to increase it until the year 2100. The price of liquid fuels would increase five-fold in the business-as-usual scenario and by a factor of 18 in the climate policy scenario. Significant parts of additional income would have to be spent in order to compensate this price increase. If the dependency on traditional biomass and fossil fuels continues it could be argued that climate policy puts a severe burden on the poorest households.

Active redistribution policy would thus be needed to allow the poorest income group to benefit from growing GDP. One option is to increase their share φ of income so that they can consume more in spite of the higher expenses for liquid fuels. An alternative option, which is line with the high electricity share in the model results (see Fig. 8), would be to expand the electricity grid. In this way, ambitious climate policy, which entails a strong shift from fossil fuels to renewables and rapid electrification, would provide the poorest part of the population with access to a cleaner and more versatile kind of energy carrier. Prices of electricity are expected to show a low rate of increase. According to our model results, the price of electricity rises only by about 10% until 2100 in the case of cooperative climate policy (Fig. 12). Electrification and grid expansion is in line with previous proposals in the literature (Casillas and Kammen, 2010). There would thus be a strong synergy effect between poverty eradication and climate change mitigation.

5 Conclusion

Climate stabilization at acceptable global costs requires contributions of developing countries to global greenhouse gas emission reductions, which may put their development perspectives at risk. Our study delivers a quantitative assessment of the costs and non-environmental benefits of global climate stabilization regimes for Sub-Saharan Africa. We show that countries in Sub-Saharan Africa could implement stringent climate policies at roughly zero net costs if international transfers facilitated by equitable burden sharing schemes are agreed upon by the international community. Revenues from the export of biomass – which is in high demand under stringent climate policies – present additional opportunities to reduce the costs of a climate stabilization regime. Net mitigation costs consequently vary between -5% and 3% across the range of analyzed scenarios.

The absence of painful trade-offs between economic development and climate protection given the commitment of the international community to an equitable burden sharing may provide policy makers with more options for climate policies than previously thought: First, low costs make joining climate stabilizations regimes more attainable for countries in Sub-Saharan Africa. Second, the potentially very regressive effects of climate policy found in our study require attention in policy design and the consideration of complementary policies. For example, there may well be synergies with poverty eradication through the provision of access to electricity.

It would be desirable to complement our analysis with case studies on specific countries of Sub-Saharan Africa and with models that emphasize the structural specifics of Sub-Saharan countries. This would allow validating the low-carbon transformation pathways we derive on an aggregated regional scale on the country level. Furthermore, it may be worthwhile to pursue more research on other climate finance options than the ones considered here. If the large transfers implied by burden sharing schemes deemed equitable should not be feasible, other ways to implement the principle of common but differentiated responsibilities, as acknowledged by the Paris agreement, will have to be found.

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