Transitions Pathways and Risk Analysis for Climate Change Mitigation and Adaptation Strategies

Energy Requirements and Feasibility of Low-Carbon Development in Africa

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TRANSrisk

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Preface

Both the models concerning the future climate evolution and its impacts, as well as the models assessing the costs and benefits associated with different mitigation pathways face a high degree of uncertainty. There is an urgent need to not only understand the *costs and benefits* associated with *climate change* but also the *risks, uncertainties and co-effects* related to different *mitigation pathways* as well as *public acceptance* of low-carbon (technology) options (or lack thereof). The main aims and objectives of TRANSrisk therefore are to create a novel assessment framework for analysing costs and benefits of transition pathways that will integrate well-established approaches to modelling the costs of resilient, low-carbon pathways with a wider interdisciplinary approach including risk assessments. In addition *TRANSrisk* aims to design a decision support tool that should help policy makers to better understand uncertainties and risks and enable them to include risk assessments into more robust policy design.

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2	Basque Centre for Climate Change	BC3	ES	
3	Cambridge Econometrics	CE	UK	
4	Energy Research Centre of the Netherlands	ECN	NL	
5	Swiss Federal Institute of Technology (funded by Swiss Gov't)	ETH Zurich	CH	
6	Institute for Structural Research	IBS	PL	
7	Joint Implementation Network	JIN	NL	
8	National Technical University of Athens	NTUA	GR	
9	Stockholm Environment Institute	SEI	SE, KE	
10	University of Graz	UniGraz	AT	
11	University of Piraeus Research Centre	UPRC	GR	
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1 ENERGY REQUIREMENTS AND FEASIBILITY OF LOW-CARBON DEVELOPMENT IN AFRICA

In this paper we investigate the prospects for the large-scale use of low-emission energy technologies in Africa. Many African countries have recently experienced substantial economic growth and aim at fulfilling much of the energy needs associated with continuing along paths of economic expansion by exploiting their large domestic potentials of renewable forms of energy. Important benefits of the abundant renewable energy resources in Africa are that they allow for stimulating economic development, increasing energy access and alleviating poverty, while simultaneously avoiding emissions of greenhouse gases.

In this study we analyse what the likely energy demand in Africa could be until 2050, and inspect multiple scenarios for the concomitant levels of greenhouse gas emissions and emission intensities. We use the TIAM-ECN model for our study, which enables detailed energy systems research through a technology-rich cost-minimisation procedure.

The results from our analysis fully support an Africa-led effort to substantially enhance the use of the continent's renewable energy potential, but they suggest that the current aim of achieving 300 GW of additional renewable electricity generation capacity by 2030 is perhaps unrealistic: we find figures that are close to half this level. On the other hand, our results indicate leapfrogging opportunities, by which renewable energy options rather than fossil fuels could fulfil most of Africa's growing energy requirements. An important benefit of leapfrogging would be that it avoids an ultimately expensive fossil fuels lock-in that determines the carbon footprint of the continent until at least the middle of the century.

1.1 Introduction

Since 1990, the Intergovernmental Panel on Climate Change (IPCC) has published a series of reports on global climate change mitigation and the large-scale deployment of renewable forms of energy needed to achieve deep cuts in greenhouse gas (GHG) emissions (for the latest editions, see IPCC, 2011 and 2014). Integrated Assessment Models (IAMs) constitute an important tool of analysis in the studies reviewed in these publications. In recent years, research groups across the world that operate these models have paid increasing attention to investigating emission reduction options and requirements at the regional level, in view of inspecting the feasibility of reaching the climate change control target to stay well below a 2°C average global temperature increase as stipulated by the Paris Agreement (COP-21, 2015). For recent studies on Africa, Asia, and Latin America, see for example, respectively, Lucas *et al*. (2015), Calvin *et al*. (2012), and van der Zwaan *et al*. (2016a).

Africa has not yet been studied as extensively with IAMs as other developing parts of the world. Among the reasons are that there are only few research teams on the African continent at present undertaking IAM scenario analysis, and that Africa's energy use to date is low, which implies that its energy future is more speculative than that of other regions. Yet Africa deserves special consideration, since among all world regions it has the highest population growth (demographic studies expect it to hold around a quarter of the global population in 2050), it proffers a large potential for economic growth, it has the most rapidly developing and changing energy system, and it is exceptionally rich in energy resources. Africa, however, is currently particularly poor in energy supply, notably Sub-Saharan Africa (IEA-WEO, 2014). According to the International Energy Agency (IEA): "*Making reliable and affordable energy widely available is critical to the development of the [Sub-Saharan] region that accounts for 13% of the world's population, but only 4% of its energy demand*" (IEA-WEO, 2014).

Because the prospects for an increase of energy use in Africa are great, this article contributes to the growing (non-IAM) literature on how modern forms of energy can be supplied to the continent while controlling global climate change through low-emission development strategies (LEDS). Through the Paris Agreement, all countries have committed to realizing substantial GHG emission reductions in the short term (COP-21, 2015). Many countries in Africa have been ambitions in this context, as formulated in their Nationally Determined Contributions (NDCs), which detail how they intend to reduce their projected business-as-usual emissions in the short to medium term (typically until 2030, but sometimes extending to 2050).

One of the present development queries is whether Africa is capable of leapfrogging the use of fossil fuels and launch energy systems that mostly rely on renewable forms of energy from the outset. We attempt to answer this question because of its environmental importance: if renewable energy (and particularly renewable electricity generation) can be used to drive economic growth, increase energy access and stimulate poverty eradication in Africa, a lock-in into fossil fuels and fossil-based power plants with a lifetime of up to half a century could be precluded.

In this paper we investigate the large-scale use of renewable energy options in Africa from a cost-optimality perspective through a well-established IAM, the TIAM-ECN model, so as to bridge a present gap in the literature in which IAMs have so far rarely been applied to Africa. One of the merits of this work is the novelty of our approach. We connect with our study to recent publications with a global focus on the challenges of renewable energy deployment (see e.g. GEA, 2012; REN21, 2016; IEA-ETP, 2016). We also contribute to work undertaken internationally to address the question of how to provide "sustainable energy for all", by making a deep dive into some of the challenges associated with this goal in Africa (UN, 2012). By focusing on the use of renewables and their ramifications in Africa, we indirectly also touch upon issues that relate to the water-energy-food nexus discussion (IRENA, 2015), given the water and food implications of e.g. most biomass-based renewable energy options. Finally, with this research we attempt to provide a reality check for the ambitions put forward by the Africa Renewable Energy Initiative (AREI), an Africa-led effort to substantially enhance the use of the continent's renewable energy potential, aiming to achieve 10 GW of additional renewable electricity generation capacity by 2020, and 300 GW by 2030 (AREI, 2015).

Section 2 of this article summarizes our methodology by concisely presenting the model used for our study and listing the references which describe it in more detail. In section 3 we report the results from our scenario runs, in terms of possible evolutions of Africa's energy system until 2050.

In section 4 we discuss these results and draw our main conclusions based on the insights that derive from our simulations, as well as attempt to provide recommendations for policy makers as well as the private sector in Africa.

2 METHODOLOGY

TIAM-ECN (the TIMES Integrated Assessment Model operated at ECN) is an energy systems model that can be employed for finding cost-minimal energy mixes based on a number of techno- and socio-economic conditions. It models energy demand and supply at the global, regional, and – in some cases – national level. In the following sub-sections a description is provided of the most important features of this scenario development tool, its inputs and outputs as well as the scenarios we ran with it, and the values that we adopted for some of its main parameters.

2.1 TIAM-ECN

TIAM-ECN is a version of the well-established TIAM model developed in the context of the IEA Implementing Agreement IEA-ETSAP, the Energy Technology Systems Analysis Program of the International Energy Agency (the energy analysis branch of the Organization for Economic Cooperation and Development (OECD) in Paris). TIAM is a member of the family of technology-rich bottom-up energy systems models based on the TIMES software platform and is described in detail in Loulou and Labriet (2008) and Loulou (2008). TIAM is a linear optimization model simulating the development of the global energy economy from resource extraction to final energy use over a period of over 100 years. Its regional disaggregation separates the world in a number of distinct geographical areas, 15 in its original format and refined to 20 a few years ago for TIAM-ECN (see Kober *et al.*, 2016). The objective function of TIAM-ECN consists of the total discounted aggregated energy system costs calculated over the full time horizon summed across all 20 regions. Running scenarios with TIAM-ECN involves minimizing this objective function.

The main cost components included in the objective function are investment costs, fuel costs and fixed plus variable operation and maintenance (O&M) costs. Other cost components such as decommissioning and infrastructure costs are also included, albeit in a simplified way. Since TIAM-ECN is based on a partial equilibrium approach with demand for energy services responding to changes in their respective prices through end-use price elasticities, savings made in energy demand and corresponding cost variations are accounted for in the objective function as well. The database associated with TIAM-ECN includes hundreds of technologies for a broad set of different sectors: for a general description of the reference energy system of TIAM-ECN see Syri *et al.* (2008). Since it encompasses all main sectors, TIAM-ECN has been used for analysis of subjects in several domains, including transportation (see van der Zwaan *et al.*, 2013a; Rösler *et al.*, 2014), power supply (Keppo and van der Zwaan, 2012; Kober *et al.*, 2016), and burden-sharing among countries for global climate change control (Kober *et al.*, 2014). Other examples of studies with TIAM-ECN – that also provide more detailed description of parts of the TIAM-ECN model – include work on global and regional technology diffusion (see for instance van der Zwaan *et al.*, 2013b; van der Zwaan *et al.*, 2016b).

In order to provide more insight into the African energy system, we have recently replaced the global disaggregation of TIAM-ECN in 20 regions by one with 36 regions, by sub-dividing the former single Africa region into 17 different geographical areas (which we will refer to as regions, even while some of them are actually countries: see **Error! Reference source not found.** and van der Laan, 2015).

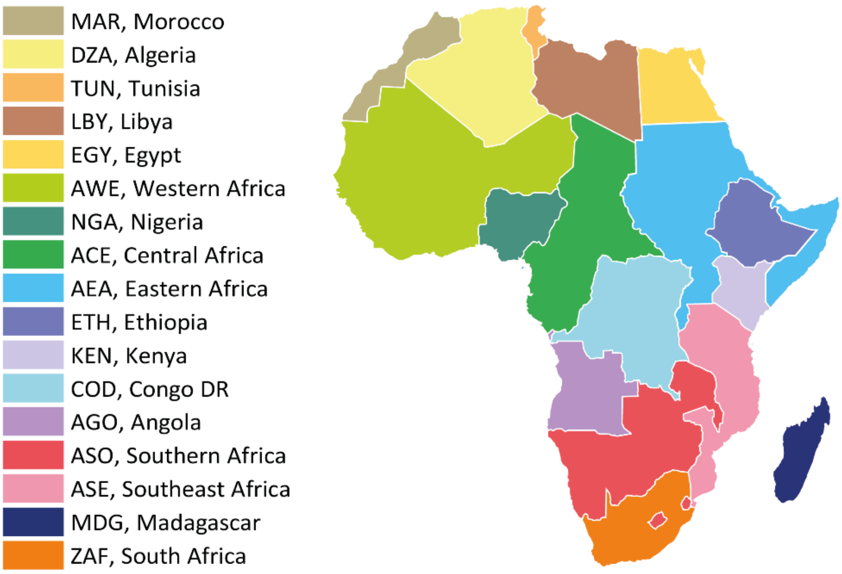

Figure 1. TIAM-ECN's geographical disaggregation of Africa in 17 regions.

Replacing the original representation of Africa as one entity by a specification of 17 distinct regions allows for a more accurate simulation of both developments that relate to the entire continent and its interactions with the rest of the world. It also enables inspection of the energy systems of individual regions within Africa in greater detail. We can thus more closely connect to the large diversity across different geographical areas in Africa in terms of, for instance, their economy, energy infrastructure, as well as political system and preparedness to address environmental challenges such as climate change. With this breakdown of Africa, we can also better analyse resource potentials, which diverge substantially across regions in Africa, both for fossil fuels and renewable energy options. This article is dedicated to Africa as a whole, and for our present purposes we have ensured that the continent's current and likely near-term energy system is represented in its entirety as realistically as possible, including the energy systems of our 17 African regions as well as the main energy-consuming sectors and energy-providing technologies therein. This allows us to effectively use TIAM-ECN for medium-term projections until 2050. Although TIAM-ECN runs over 100 years, due to the rapid changes in the African energy system we focus in this study only on the time frame until 2050.

Our modelling efforts involve various types of shortcomings and uncertainties, and their results should not be interpreted as forecasts, but projections of possible outcomes or storylines instead.

2.2 Inputs, outputs, and scenarios

TIAM-ECN is operated under input assumptions on policy measures, technology features, resource data and demand projections, while delivering outcomes in the form of policy recommendations, technology portfolios, energy (trade) flows and investment & price levels (see Figure 2 for a schematic diagram). With these inputs respectively outputs, TIAM-ECN allows for performing cost-based analysis under multiple scenarios. For the purpose of the present study, we run four different scenarios. The first one is a reference (that is, 'baseline' or 'business-as-usual') scenario, called REF, in which current developments are extrapolated and fossil fuels continue to contribute the largest share of total energy supply. This scenario is a representation of what Africa's energy system may look like without the introduction of far-reaching climate policy. The second one is a stringent climate change control scenario, entitled 2DC, which implies a high likelihood (of around 70%) that the global average atmospheric temperature increase does not exceed 2ºC. For this scenario we assume that the additional (anthropogenic) atmospheric radiative forcing does not exceed 2.6 W/m^2 (i.e. the representative concentration pathway RCP2.6, in terms of the IPCC (2014) terminology). The third one is a climate policy scenario in which we assume that a global carbon market is established with a CO_2 price increasing with a rate of 4%/yr from 50 US$/t$CO_2$e in 2020 to over 160 US$/tCO_2e in 2050 (scenario TAX). The fourth one is a climate policy scenario in which global GHG emissions are reduced by 20% in 2050 with respect to 2010 (scenario CAP).

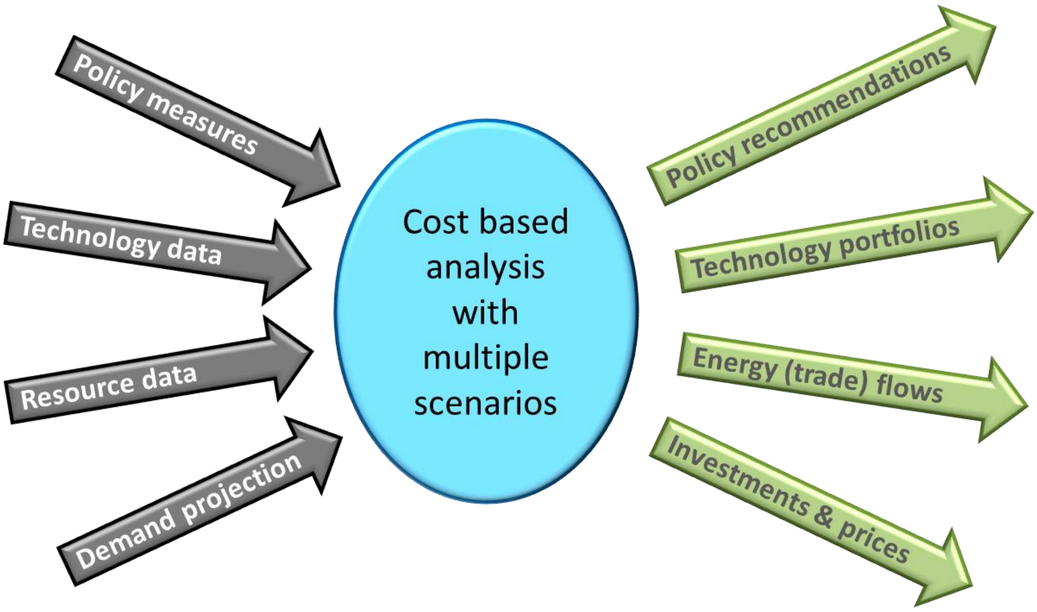

Figure 2. Stylistic representation of the main inputs and outputs of TIAM-ECN.

2.3 Main assumptions

As with any model, the outcome of scenario runs with TIAM-ECN is determined by the values of its input parameters, which is why our results should not be interpreted as forecasts, but rather as projections of how the energy system could possibly develop in the future. For each technology simulated in TIAM-ECN across all main energy-producing and energy-consuming sectors of the economy, assumptions are made on e.g. their current costs, future cost changes, maximum penetration rates and conversion efficiencies. Energy demand projections are made on the basis of expectations regarding socio-economic factors such as population growth, welfare increase, and the realisation of savings and the implementation of efficiencies. Other assumptions relate to, for instance, fossil fuel reserves in different parts of the world, renewable energy potentials, energy trade capabilities between regions (see Schuler, 2016), autonomous energy efficiency and decarbonisation processes, as well as energy-climate policies implemented prior to the reference year at which TIAM-ECN is calibrated (2010). For details on these assumptions, see the publications above.

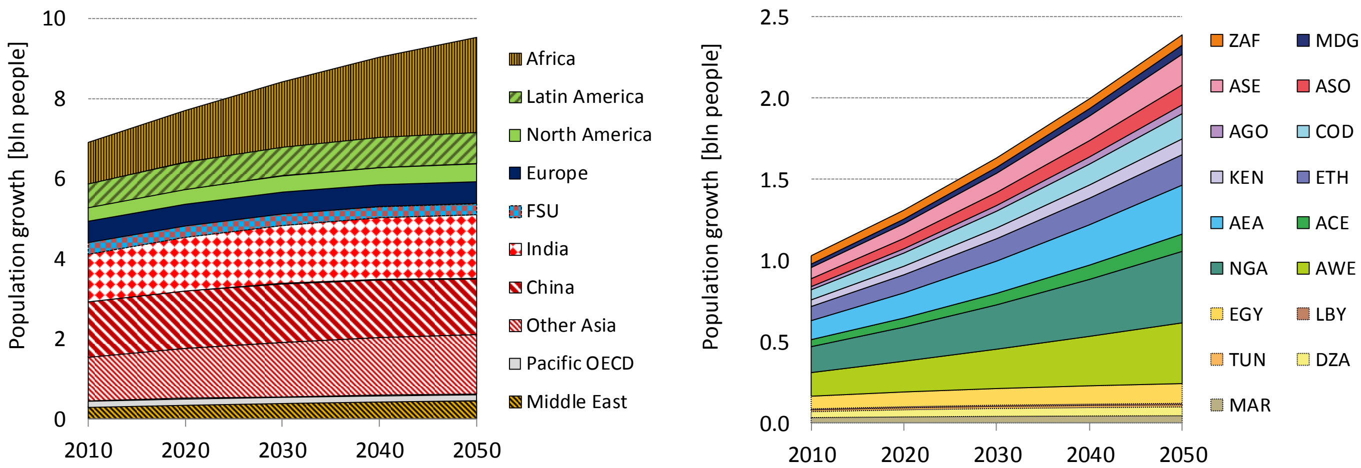

Figure 3. Population growth for the major economies in the world (left) and demographic breakdown for the 17 regions in Africa (right) as simulated in TIAM-ECN.

Figure 3 (left plot) depicts our estimates on global population growth and provides details on the demographic change patterns for all major regions and economies in the world. As can be seen, our central inference on expected population growth in Africa is an increase by about a factor of two by the middle of the century. In this time frame, Africa thus experiences by far the highest population growth among all world regions, outpacing notably India as well as other fast-growing parts of Asia. In the right plot of Figure 3 we show our population growth assumptions for each of the 17 African regions represented in TIAM-ECN. As can be observed, for some countries – notably in West and East Africa – our supposed population increase may be as high as a factor of three over the time frame considered. For many other Sub-Saharan countries it is about a factor of two, while for the Maghreb area of the continent we expect population growth generally to be lower (but this may still imply significant demographic expansion, such as in the case of Egypt, which sees its population grow from around 90 million in 2010 to close to 120 million in 2050).

Economic growth for Africa as a whole, measured in terms of aggregated GDP, is assumed to be around 7%/yr in 2010, dropping to somewhat below 5%/yr by 2050. For individual countries and regions we suppose a spread of growth values a couple of percentage points above and below these levels, respectively. As a result, the aggregated African economy expands by more than six-fold over the time frame of our scenario runs. Given the expected doubling of the population on the continent, GDP per capita 'only' increases three-fold over this period (see Figure 12 in the Appendix, in which we point out that Africa still ranks lowest among all regions in terms of GDP per capita by the middle of the century).

3 RESULTS

Figure 4 (left plot) shows that global GHG emissions (including CO_2, CH_4, and N_2O, but excluding other GHGs) in the REF scenario increase steadily from their 2015 level of approximately 50 $GtCO_2e$ ($GtCO_2$-equivalent) to a value of approximately 40% higher by 2050. Under the three climate policy scenarios, global emissions are substantially curtailed, especially when the objective of limiting the average atmospheric temperature increase to 2°C is achieved (2DC), for which they are reduced to around 40% with respect to the 2015 level. For Africa as a whole (right plot) we observe mostly similar results, notably in terms of the ranking of the four scenarios, but for two main differences. First, reference GHG emissions in Africa rise much faster than for the world, by about 100%, as a result of substantially higher than global average population and economic growth. Second, the three climate policy scenarios show no decrease in emissions during the first half of the century (for TAX and CAP one can actually observe a significant increase, by 30% to 40%, respectively), which is another expression of the rapid increase of GHG emissions in Africa in the REF scenario. A clear common feature of the two graphs is that the TAX and CAP emission pathways are quite similar.

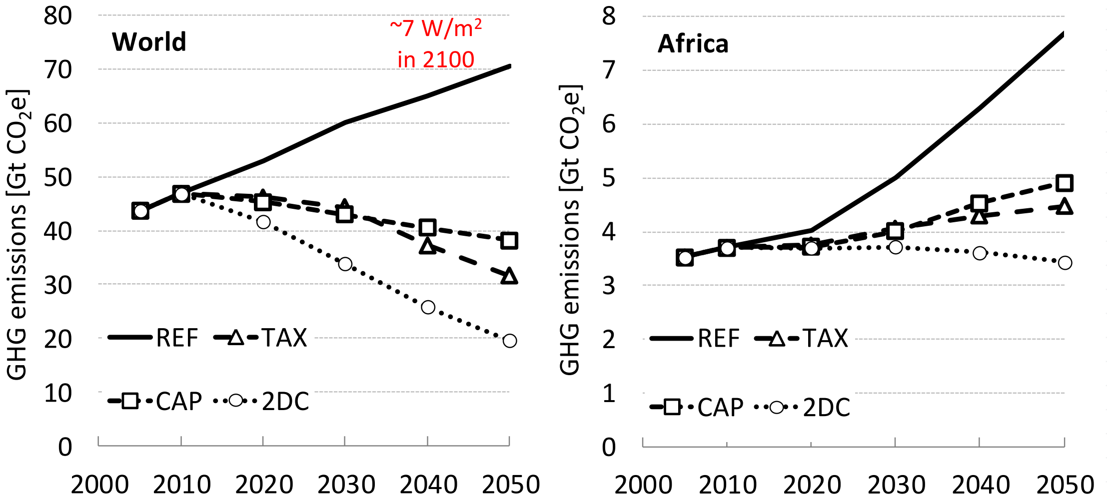

Figure 4. GHG emissions in the world (left) and Africa (right) in our four scenarios.

In Figure 5 we see for Africa the same type of information (i.e. GHG emission developments) as depicted in Figure 4 (right plot), but broken down by type of GHG. As can be observed by inspecting, for example, the cluster of four scenario bars for 2050 in Figure 5, CO_2 emissions can be reduced more easily as a result of climate policy than emissions of CH_4 and N_2O under our cost-minimisation structure. The explanation is that in e.g. the power sector more means exist to abate GHG emissions than in agriculture, and abatement costs for CH_4 and N_2O emissions in the latter are relatively high in comparison to CO_2 emissions abatement costs for electricity generation. Note that this graph is expressed in $GtCO_2e$ terms: in volume terms CH_4 and N_2O are emitted one to two orders of magnitude less than CO_2. If one compares the emission levels of CH_4 and N_2O between 2010 and 2050, an increase can be observed for both these gases independent of the scenario considered. This does not imply, however, that agriculture (from which most CH_4 and N_2O emanates) has not been subject to substantial progress. Quite on the contrary, in TIAM-ECN we assume multiple resource efficiency improvements for agriculture (such as related to waste management and the use of fertilizers) that materialize over the next decades in Africa. Rather, what we see here is that the increase in demand for agricultural products as a result of population and economic growth is so overwhelming that it out-shadows, in CH_4 and N_2O emission terms, the mitigating effects of agro-technological progress. An insight from Figure 5 is that in a reference scenario, the largest contribution to climate change in Africa until 2050 continues to derive from CO_2, while under climate change control policy the relative weight of CO_2 gradually decreases. Under a 2DC scenario, the situation reverses: CH_4 and N_2O combined yield the majority of Africa's climate change footprint in 2050. In the Appendix we show how the CO_2, CH_4, and N_2O emission intensities per capita (and their evolution over time) compare to their global average equivalences.

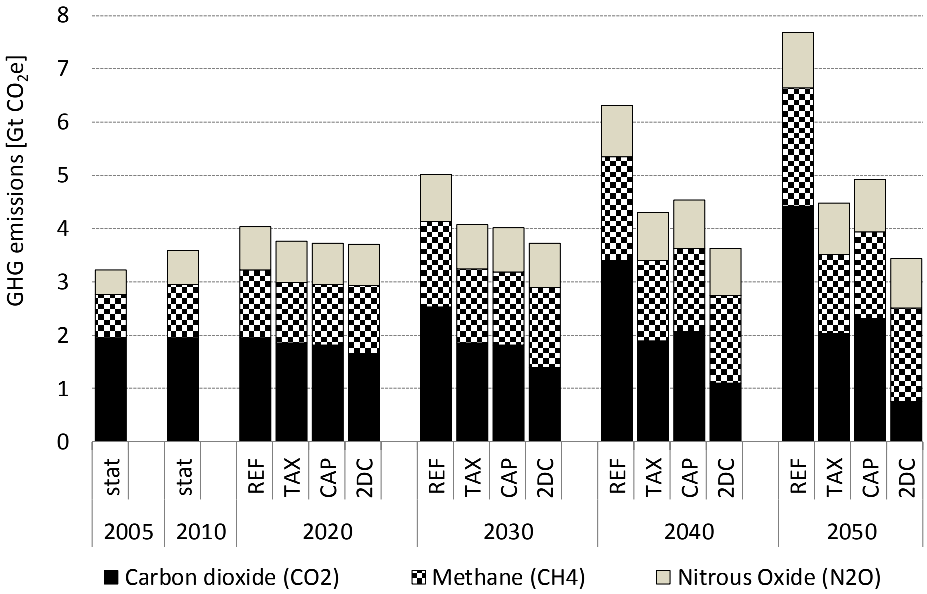

Figure 5. Breakdown of GHG emissions in Africa in our four scenarios.

Figure 6 zooms in on the evolution of CO_2 emissions in Africa under our four scenarios. As can be seen, power generation gradually decarbonizes until it is close to carbon-free in 2050 in the TAX and CAP scenarios, while in the 2DC scenario it turns carbon-free around 2040. Emissions of CO_2 in industry continue to play a role in all scenarios until 2050, although in the 2DC scenario the contribution becomes negligibly small from about 2040. Emissions of CO_2 from the residential sector rise despite climate policy, except in scenario 2DC, where it becomes essentially carbon-free in 2050. Emissions of CO_2 in the commercial and upstream sectors, as well as in agriculture, remain very small throughout this time frame, but large CO_2 emission changes take place in land-use and transportation. Land-use CO_2 emissions are substantially curtailed in all cases, including the reference scenario (mostly based on arguments of environmental protection). Emissions of CO_2 in the transport sector increase over the forthcoming decades in all scenarios, even in 2DC.

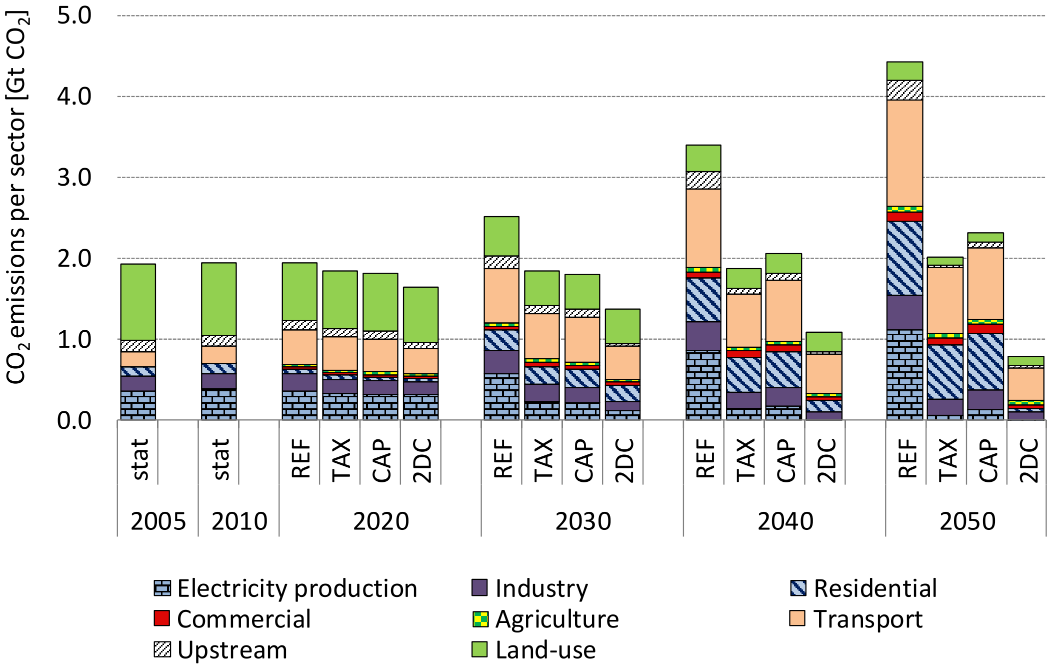

Figure 6. Breakdown of GHG emissions in Africa in our four scenarios.

Most of our outcomes are driven by relative abundances or shortages of cheap emission reduction options in these respective sectors. The bar for the 2DC scenario in 2050 shows that if the implemented climate policy is stern enough, climate change mitigation targets are also realised in areas where abatement technology is usually quite costly, such as in industry. We see that 2DC is the only scenario in which CO_2 emissions in 2050 are below the ones today, by more than a factor of two. Yet the structure of these emissions is fundamentally different: while about half of all CO_2 emissions in 2010 derived from land-use, in 2050 transportation accounts for about half.

Fossil fuels – the source of an important share of Africa's CO_2 emissions – play a large role in the overall energy supply of Africa, and are likely to do so under all scenarios that we investigate. This is demonstrated in Figure 7 that depicts all the main energy resource types that contribute to total primary energy consumption on the African continent. As can be seen, renewables account for about half of primary energy usage today, mostly in the form of biomass.

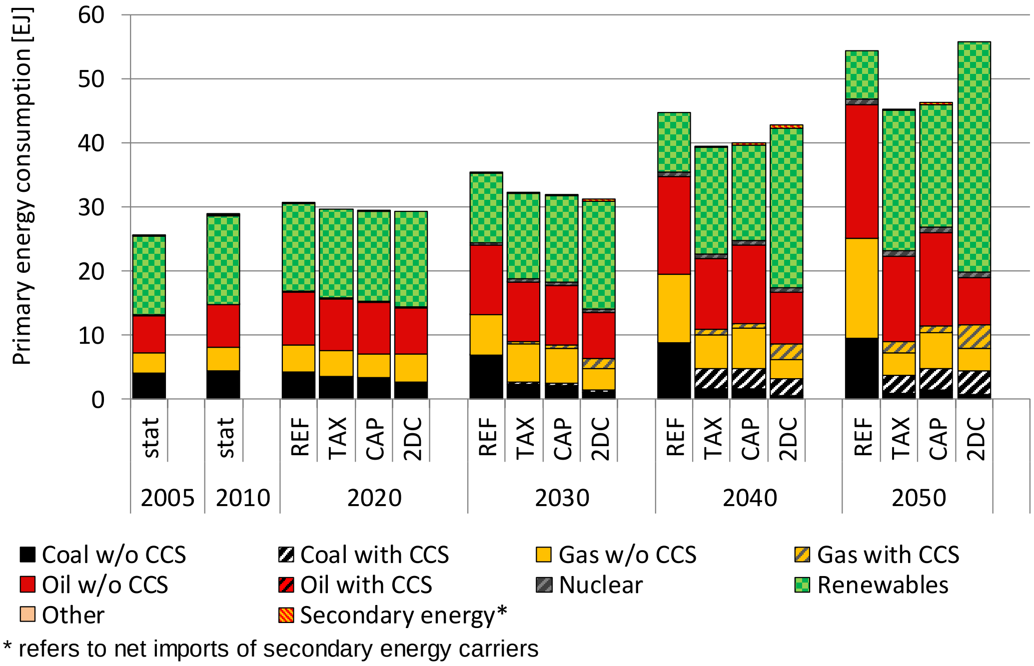

Figure 7. Primary energy consumption with resource breakdown in Africa in our four scenarios.

Figure 8 depicts the TIAM-ECN results for the intensity per capita of CO_2 emissions from fossil fuels and industrial activities (FF&I) against the primary energy intensity per capita for five major economies in the world, as well as the global values for these variables. Note the log-log scale of both graphs, which, compared to a linear-linear scale, depicts relative rather than absolute levels of change in these variables, therefore highlighting the magnitude of emission reduction efforts over time with respect to a unique starting point for each region. The left plot describes their evolution from 2005 to 2050 under our REF scenario, whereas the right plot does so for the 2DC scenario.

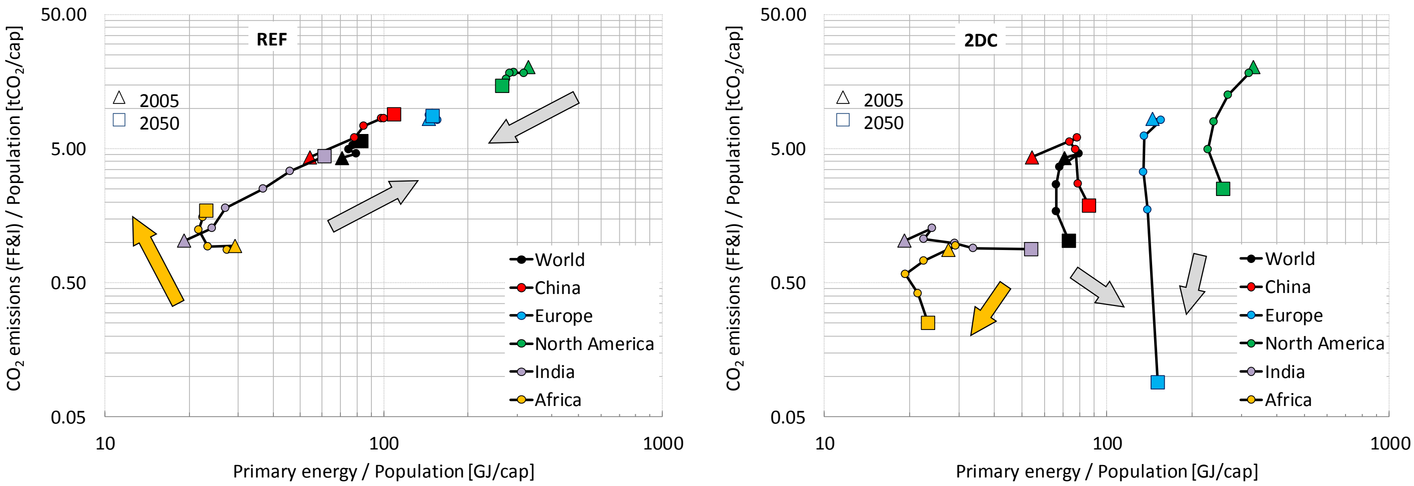

Figure 8. CO_2 emission intensity against primary energy intensity for five major economies, and their global values, under the REF (left) and 2DC (right) scenarios.

As seen from Figure 8, the dynamics under the REF scenario (left plot) generally play out along the diagonal, implying a coupling between energy and CO_2: in North America both CO_2 and energy intensities decrease. While for China, India and the world at large they increase, converging on the relatively stable point for Europe. For Africa, these intensities evolve quite differently. Until 2020 the energy intensity drops significantly, under an almost constant CO_2 intensity, while from 2020 to 2050 the CO_2 intensity doubles under nearly stable energy intensity levels. Until 2020 we essentially see the predominance of population growth over that of energy use increase and associated CO_2 emissions. From 2020, economic growth and associated increases in energy demand catch up with demographic growth so as to yield a stable energy intensity until 2050. During these decades, an increasing share of energy requirements is fulfilled with fossil fuels, which explains the rise in CO_2 emissions intensity from 2020 onwards.

In the 2DC scenario (right plot of Figure 8) we see that all lines towards 2050 point downwards as a result of the stringent climate policy that complies with the Paris Agreement goal of staying within a temperature increase limit of 2ºC. For Europe and North America (as well as for the world as a whole) we see substantial improvements in CO_2 intensity under relatively constant energy intensity values. For China, we see an increase in both the energy intensity and CO_2 intensity until 2020, while from 2020 onwards there is a substantial drop in CO_2 intensity (under a quite stable energy intensity). For India, one observes on average an almost unchanging level of CO_2 intensity throughout our period of study, but nearly a tripling of the energy intensity. For Africa, we see that our indicators develop quite differently from what occurs in the rest of the world. Unlike for other developing regions, we find a drop in energy intensity in Africa until 2030, which is partly an effect of steep population growth, and partly the phasing out of several traditional forms of energy use (such as in cooking stoves). For both China and India we observe a substantial increase in energy intensity over our time frame. Between today and 2050 the CO_2 intensity in Africa falls by about a factor of seven, thanks to a massive deployment of renewables, while for China it falls by a factor of 5 and for India remains unaltered.

Africa's development and its 'climbing the energy ladder' is a slow process that will not have been completed by 2050. The process will play out during the latter half of the century, when incomes will rise and eventually per-capita energy consumption will grow from 20-30 GJ/capita where it has stalled until 2050 to a value closer to 100 GJ/capita as in the rest of the world. The TIAM-ECN scenarios project a drop of per capita energy use, driven by technology improvement and ensuing gains in energy efficiency (such as for cook-stoves) as well as by a rapidly growing population that moderates per capita increases in both of these parameters, even as both GDP and total energy use grow substantially. Although Africa's gradual development over the next decades materializes at a level of per capita emissions and energy use that is tenfold lower than in industrialised countries, the extent to which emissions per capita reduce in Africa during the first half of the century, as expressed in the right plot of Figure 8, resembles that of the transition the developed regions in the world are projected to go through, more so than the way China and India currently develop. This may be an indication of potential to leapfrog over a carbon- and energy-intensive economy directly towards one in which renewables and energy efficiency play a dominant role. Different regions in Africa may develop quite distinctly, but for Africa in average our findings stand out quite clearly.

Note that the fact that the CO_2 intensity in Europe falls much deeper than in the US is mostly a matter of timing. For both the European and American economies we observe an accelerating decrease in their CO_2 intensity. In the case of the US, however, it is at a higher starting level than for Europe. The US decreases its CO_2 intensity by close to an additional order of magnitude in the decade following 2050, like Europe does during the last decade (2040-2050) of the time frame considered in this study. In the Appendix (Figure 14) we show similar plots as the two depicted in Figure 8, but with the denominator 'per capita' replaced by 'per unit of GDP'.

Figure 9 shows the deployment of renewable energy options in Africa to meet primary energy demand under our four scenarios until 2050. In the reference scenario, we observe a gradual decline of the use of renewables as a result of the phasing out of traditional biomass options (mostly in solid form, such as charcoal for cooking and heating purposes). As can be seen, part of the original biomass usage pertains, but traditional biomass options are substituted by modern biomass-based technologies. Modern forms of biomass usage include notably solid, liquid, and gaseous biofuels used for electricity generation (used e.g. for the replacement of traditional cooking in stoves, but applied for usage across many applications in the energy system). Much of the modern biomass-based electricity generation is centralized, usually located outside cities. The co-benefit hereof is that much of today's inner-city air pollution can be avoided. Modern high-efficiency biomass technologies also yield enhanced forest preservation benefits, and obviate traditional firewood collection.

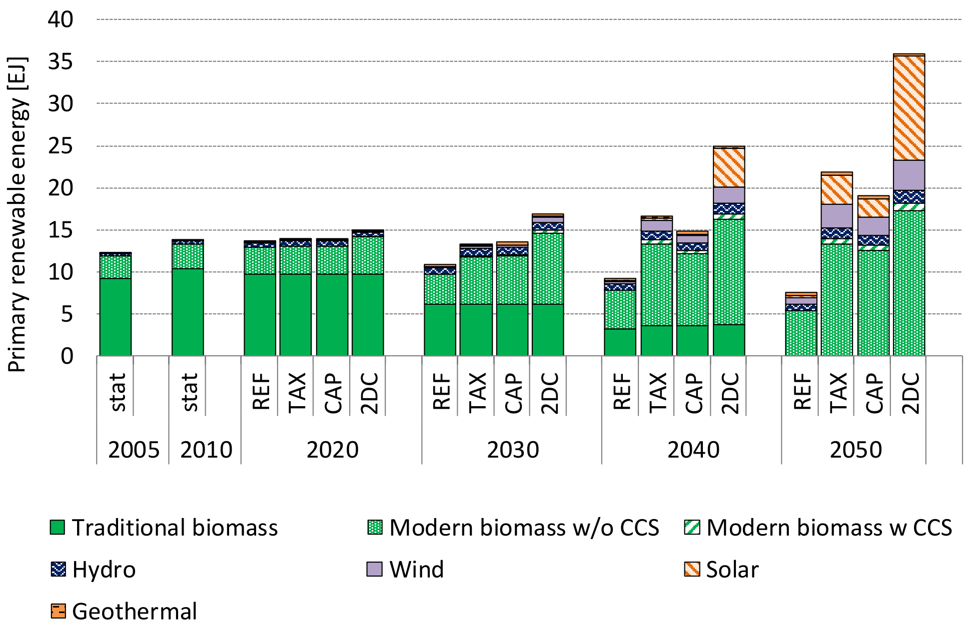

Figure 9. Primary renewable energy deployment in Africa under our four scenarios.

For the climate change control scenarios, on the other hand, we see that the use of renewables increases strongly, not only because of an increased use of biomass in modern energy applications with respect to the reference case, but especially as a result of the widespread deployment of several other renewables such as solar and wind energy technologies. Notably, solar power becomes an essential part of the African energy system in the 2DC scenario. We also observe an enhanced generation of hydro-electricity, on the basis of the large hydropower potentials in a number of African countries. Although not clearly visible in the Figure, geothermal energy also plays a role at the %-level in a couple of decades from now, given the geothermal resources in several countries in e.g. the Rift Valley region.

The way in which electricity demand, and correspondingly supply, increments exponentially in Africa under each of our four scenarios is plotted in Figure 10. In the reference case, coal and gas based electricity generation accounts for the majority of all power supply until the middle of the century, while in the three climate policy scenarios the use of fossil fuels for power supply is substantially curtailed. In the climate change control scenarios, on the other hand, renewable electricity generation technologies are implemented on a large scale, including biomass-based, hydro, solar and wind power. We see gradually also an increasing role for CCS applied to coal and natural gas based thermal power plants, especially in the 2DC scenario. In all scenarios a small share is reserved for nuclear power, although it is produced in one country only, South Africa.

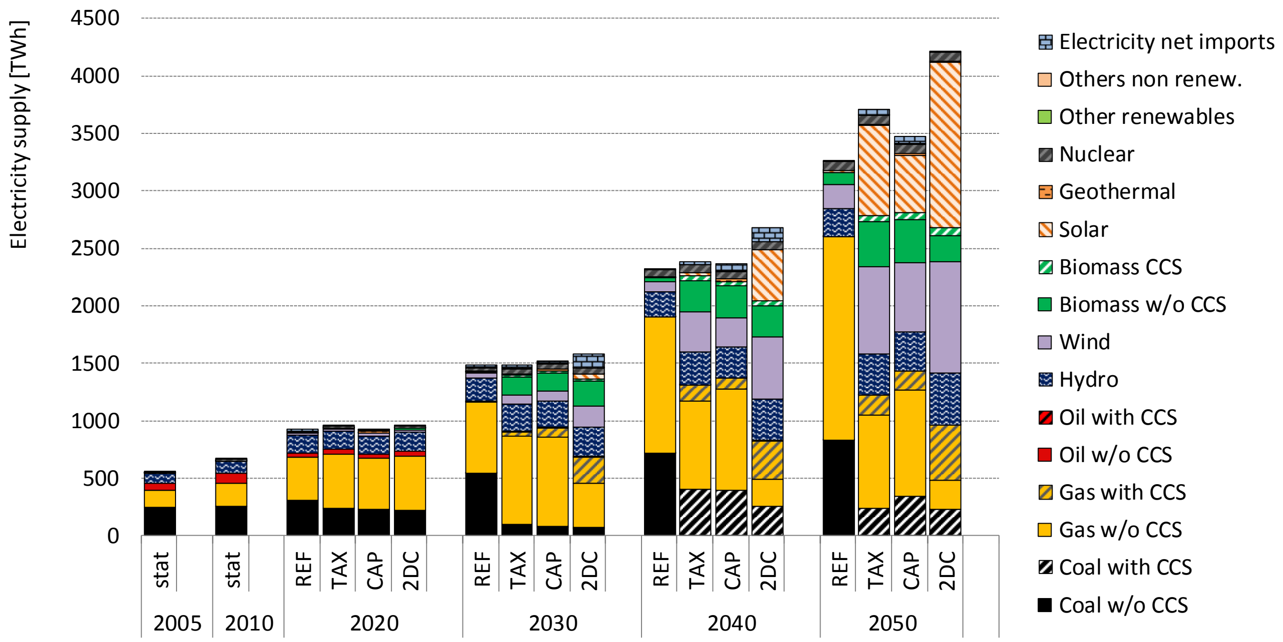

Figure 10. Electricity supply in Africa under our four scenarios.

The medium-term (2030-2050) prospects for additions in power capacity constitute an indicator for the public and private activities correspondingly required in the electricity sector. These are reported in Figure 11, and expressed as annual averages in GW/yr, under the 2DC scenario. We compare the numbers obtained with TIAM-ECN plotted in the right part of the Figure ('Future'), to values materialized in the past as observed in Africa, the EU and Latin America ('History'). As one can see from this Figure, in the medium-term Africa will need capacity deployment for options like natural gas, wind and solar energy based electricity generation at rates that are multiple times higher than the maximum values reached in the past for either fossil-based or renewable power options in the EU and Latin America. Figure 11 constitutes a complementary way of articulating the magnitude of the energy-climate challenge for Africa over the next several decades. As this Figure shows, options such as hydropower and biomass-based electricity generation also play a sizable role in providing electricity to Africa in the medium term, as do coal and gas-based power plants equipped with CCS technology, albeit at a much lower scale in GW terms than wind & solar power and conventional (non-CCS) gas-based electricity production.

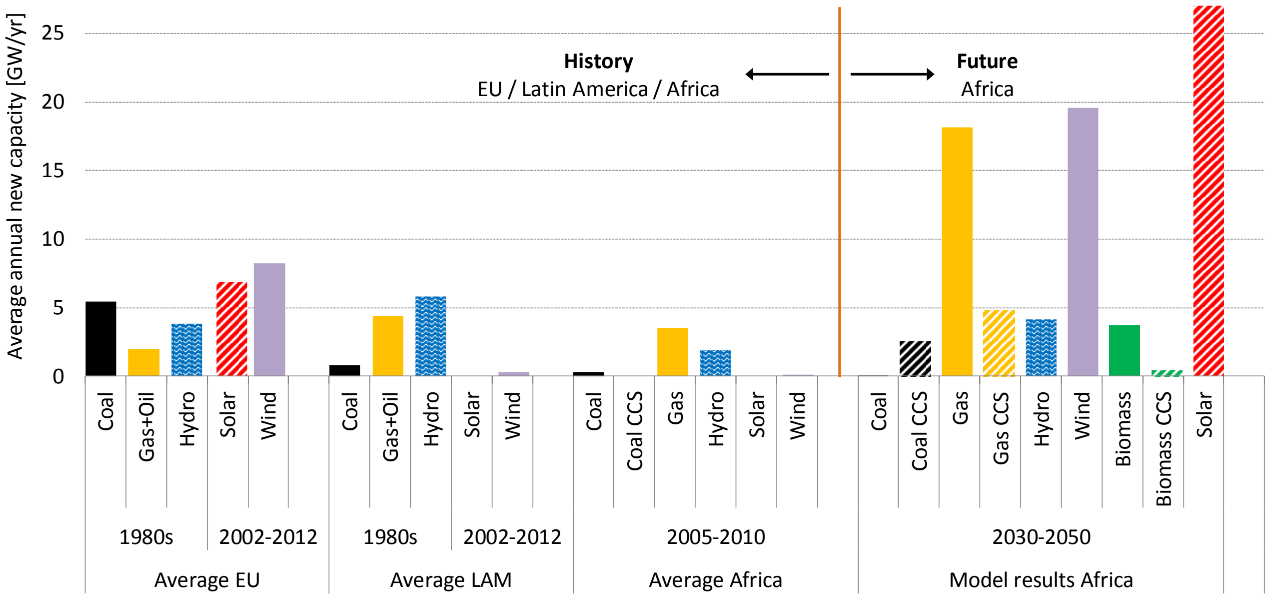

Figure 11. Electric power capacity additions: past for Africa, EU and Latin America, and prospects for Africa under the 2DC scenario.

We note that these are model-based outcomes, premised on rational deployment of technology to deliver energy services at lowest cost under certain policy constraints (such as in the 2DC scenario). Our model does not take into account important factors like cultural preferences and institutional capacity. For instance, the deployment of CCS may be economically rational, but it requires a resolve and ability that the developed world has not yet mustered. Considerations of this kind may well favour wind and solar power even more than indicated by our scenario runs. But whatever the type of new forms of energy supply, Figure 11 shows that even in a scenario where per-capita energy use does not rise, the investments to modernize (that is, to electrify) energy usage in Africa will require a massive step-up in investments in electricity production capacity, from about 5 GW/yr in 2005-2010 to more than 50 GW/yr within a few decades.

4 Discussion, Conclusions and Policy Implications

An explicit goal of the Africa Renewable Energy Initiative (AREI) is to help African countries to leapfrog towards renewable energy systems in support of their low-emission development strategies (AREI, 2015). In this article we report evidence for the feasibility of leapfrogging from an energy-system cost minimisation perspective. Our analysis of multiple scenarios reveals that, in order to meet the given targets, it is optimal to preclude the use of CO_2-emitting technologies in Africa, and massively deploy renewable options instead, for a rapidly growing energy sector. This can only be achieved if stringent climate policy is in place – it wouldn't come like manna from heaven. We conclude, however, that AREI's target of an additional 300 GW of renewable power production capacity by 2030 is probably unrealistic. Even in our most ambitious scenario (2DC), about half of this figure is reached at most.

Today, Africa contributes less than 8% to global emissions of approximately 50 $GtCO_2e$ for the three most important GHGs (CO_2, CH_4, and N_2O). We find that if attempts fail to implement an international climate change control regime, and GHG emissions continue to rise over the coming decades as in our reference case, Africa's share will only be slightly above 10% of global GHG emissions by 2050, even if it develops at an average economic growth rate of 5%/yr and doubles its population over this time frame. If a strict emissions reduction pathway is followed by which the global average temperature increase is limited to 2ºC, Africa's part in global emissions could be as high as 18%, similar to the current US contribution to total emissions. Hence in this case Africa could become one of the major GHG-emitting economies in the world by around 2050.

This paper has several features in common with a recent publication on a similar subject by Lucas *et al*. (2015), and shares a number of its conclusions. We also focus on Africa's role in the global energy system, against the backdrop of international efforts to control climate change. The strength of their article is that they use a set of different IAMs (including an older version of TIAM-ECN), which allows for an inter-model comparison study. We here use one IAM only. Our present study's merit is that TIAM-ECN has now a more detailed geographical disaggregation for Africa than any of the models used in Lucas *et al*. (2015), and it has been updated to better represent the divergences in projections of the African energy system and regional population and economic growth. The work by Lucas et al. (2015) used an existing database with previously established model runs, generated in the LIMITS project (2011-2014), for which no African energy system simulation improvement was undertaken. We agree with Lucas *et al*. (2015) that renewable energy options possess great deployment potential. Our current results disagree, however, with their finding that CO_2 emissions in Africa are not likely to become significant on a global scale before the year 2050 – we conclude that in certain cases GHG emissions could actually become substantial.

Like in Latin America, non-CO_2 emissions contribute substantially more to the overall GHG balance in Africa than in other parts of the world. At present, close to 40% of GHG emissions in Africa and Latin America – expressed in $GtCO_2e$ – derive from CH_4 and N_2O, against at most 20% in the EU and US (the world average figure is around 25%; see e.g. Clarke *et al*., 2016). Under our stringent climate policy scenario (2DC), CH_4 and N_2O emissions in Africa contribute around 80% to the total climate change footprint in 2050, while substantial improvements are achieved in the intensities per capita for all GHGs. The explanation is that abatement of CO_2 emissions can be reached more easily and less expensively than reductions in CH_4 and N_2O emission, which results in decreases of the former being realised earlier and more aggressively than for the latter. Today half of all CO_2 emissions in Africa, around 1 $GtCO_2$/yr, derive from land-use (change). In 2050 we project this to fall to 0.1-0.2 $GtCO_2$/yr, irrespective of the (reference or climate policy) scenario considered.

Primary energy consumption in Africa is likely to remain below 30 GJ/cap until 2050, irrespective of the scenario we inspect. For India, this figure is likely to be twice as high and in the EU and US values amount to some 150 GJ/cap and 250 GJ/cap, respectively. With a carbon intensity of around 2 tCO_2/cap in 2050 in the reference case, Africa stays a factor of 2 below the level reached by India, and a factor of 4 below that in China. With a projected carbon intensity of some 0.25 tCO_2/cap in 2050 in the 2ºC scenario, Africa stays a factor of 4 below the number attained in India, and 8 times below that in China. In other words, whatever the scenario, we find that Africa, in per capita terms, continues to contribute substantially less to global CO_2 emissions than any other region in the world.

The use of renewable energy resources such as hydro, solar and wind power receives a major impetus under stringent climate change control. We conclude that biomass experiences a turn-around, as its use in carbon-intensive (non-sustainable) ways for e.g. cooking and heating is replaced by low-carbon (sustainable) usage in many sectors. Our estimate is that in 2050 the consumption of biomass increases by as much as 40% in our most stringent climate policy scenario, in comparison to today. This increase, and the fundamentally different way in which biomass will be employed, inexorably augments the demand for good governance.

We find that electricity generation provides a powerful way to mitigate climate change: the African power sector expands six-fold in four decades in our 2DC scenario, that is, more than the close to five-fold growth that our model generates for the reference case. The associated additions in average annual capacity required for options like solar and wind power, as well as natural gas based electricity generation, are in the medium term (2030-2050) two to three times higher than the values observed in the past in the EU. Such expansion proffers business opportunities for industry, as well as environment and health co-benefits, while creating challenges regarding investment and institutional requirements.

Our study supports two UN Sustainable Development Goals (SDG, 2015), no.7 (affordable and clean energy) and no.13 (climate action), and possesses strong relevance for at least three others, no.1 (no poverty), no.8 (decent work and economic growth), and no.11 (sustainable cities and communities). We demonstrate that these SDGs are mutually compatible. For example, the 2DC scenario allows for exponential economic growth (SDG 8) and achieves a switch from traditional to modern biomass for about 1 billion people in Africa today – around 2 billion in 2050 (SDG 7) – along with a substantial decrease of the carbon intensity of the continent's energy system (SDG 13).

The expansion of renewable electricity generation in all climate policy scenarios (TAX, CAP, and 2DC) yields large opportunities for job creation in the low-carbon energy technology sector, but enhanced power production capacity requires unprecedented levels of investment. This constitutes a challenge for Africa, where the availability of public funds is often limited, and where governments have sometimes little experience with renewable energy investments and the policies needed to stimulate them. A solution could come from private investments. In particular, private-public partnerships (PPPs) can be effective in raising capital for investments in renewable energy, and could provide the necessary technical and financial expertise. In South Africa, for instance, the 'South African Renewable Energy Independent Power Producer Procurement Programme' is a PPP that has achieved electrification of rural areas through renewable energy investments (Eberhard *et al.*, 2014). Since 2011 more than 100 renewable energy projects have materialized, totalling a capacity of around 6 GW, which has led to some of the lowest costs for renewable electricity production in the world. If other African countries are to follow this example, governments will have to improve their guarantees of clear, consistent, and transparent regulation with regards to renewable on- and off-grid energy.

APPENDIX

Figure 12 shows the TIAM-ECN assumptions for the main regions in the world regarding growth of GDP per capita, based on e.g. data from the World Bank (WB, 2016). Based on our assumptions, we see that Africa in 2050 still ranks lowest among all regions in terms of GDP per capita. This is an expression of the fact that in our projections high economic growth in Africa does not compensate for expected population growth so as to yield a GDP per capita in 2050 that approximates that of other developing regions.

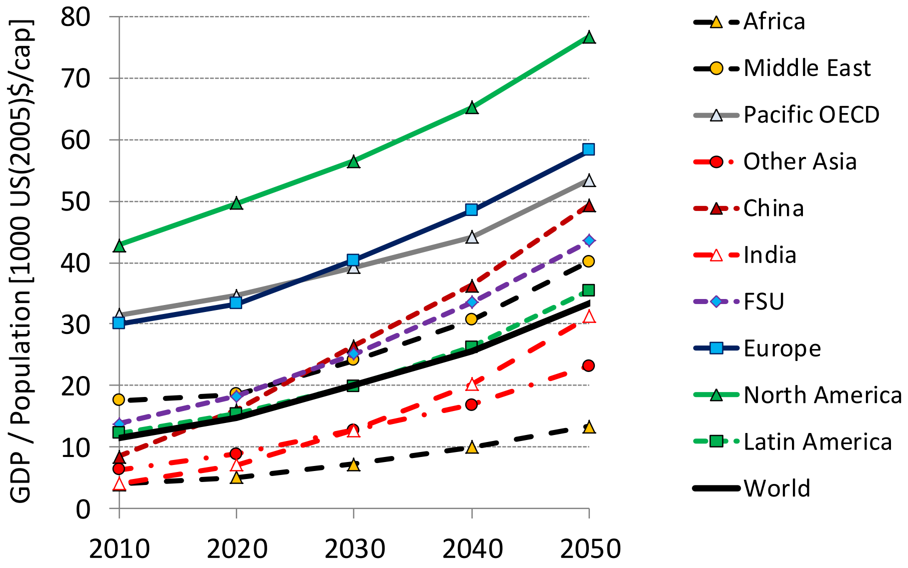

Figure 12. Projected growth of GDP per capita for the major economies in the world.

In Figure 13 we show how the CO_2, CH_4 and N_2O emission intensities per capita change over time, in the left graph for the REF scenario and in the right graph for the 2DC scenario (note that both graphs are double-logarithmic, and that emissions are expressed in tCO_2e terms). We plot the average intensity values for the world against those for Africa, which allows for inspecting the extent to which Africa deviates (or not) in this respect from world tendencies. In the REF case, we see that the average CO_2 intensity is several times higher for the world than for Africa, and that little changes over time with its value. Their CH_4 intensity is pretty much similar and remains largely unaltered. For the N_2O intensity, we see an interesting development: while for the world little changes until 2050, its value reduces by about a factor of two in Africa, mostly as a result of efficiencies introduced in agriculture. In the 2DC case, one observes a drastic reduction of per capita CO_2 emissions, for the world in a similar way as for Africa (hence the blue line is parallel to the diagonal). The CH_4 emissions intensity improves likewise in a parallel way to (in this case on) the diagonal. For N_2O we see that the red line remains below the diagonal, which is an expression of the fact that substantial progress in agriculture in Africa (e.g. through improved fertilizer usage) is complemented with agro-technological advance in the world at large (through a variety of means such as automation).

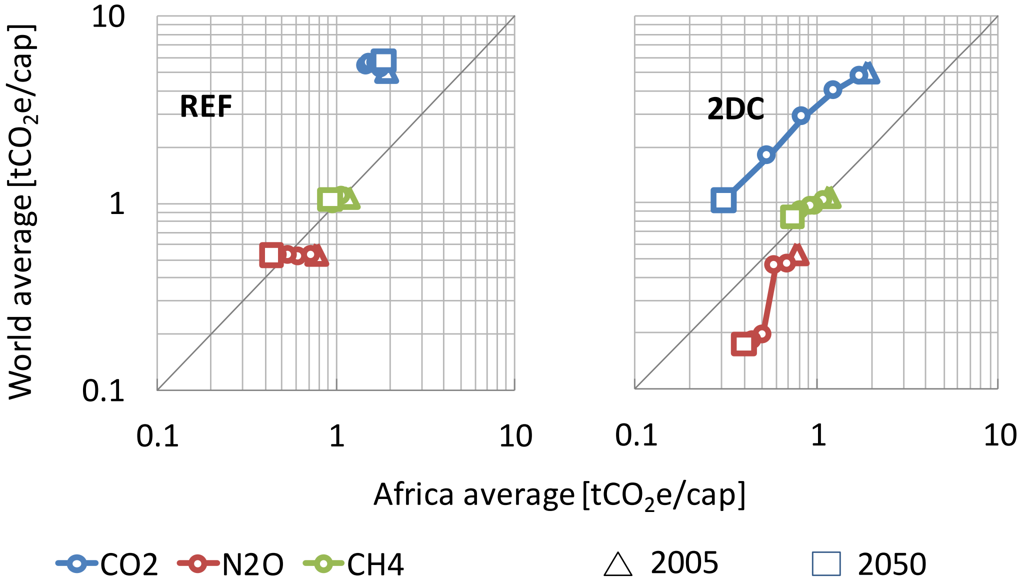

Figure 13. Average CO_2, CH_4 and N_2O emission intensities per capita, and their evolutions until 2050, for the world against Africa under the REF (left) and 2DC (right) scenarios.

Figure 14 depicts the TIAM-ECN results for the CO_2 emission intensity per unit of GDP against the primary energy intensity per unit of GDP for five major economies in the world as well as the global values for these variables (note the linear scale of both graphs). The left plot describes their evolution from 2005 to 2050 under our REF scenario, whereas the right plot does so for the 2DC scenario. From Figure 13 it can be observed that for the CO_2 and energy intensities per unit of GDP in the REF case there is gradual convergence in 2050 for all major economies (and thus the world) towards values in the range of 100-200 gCO_2/$ respectively 2-4 MJ/$. In the 2DC case the convergence band widths are 0-50 gCO_2/$ and 2-4 MJ/$, respectively.

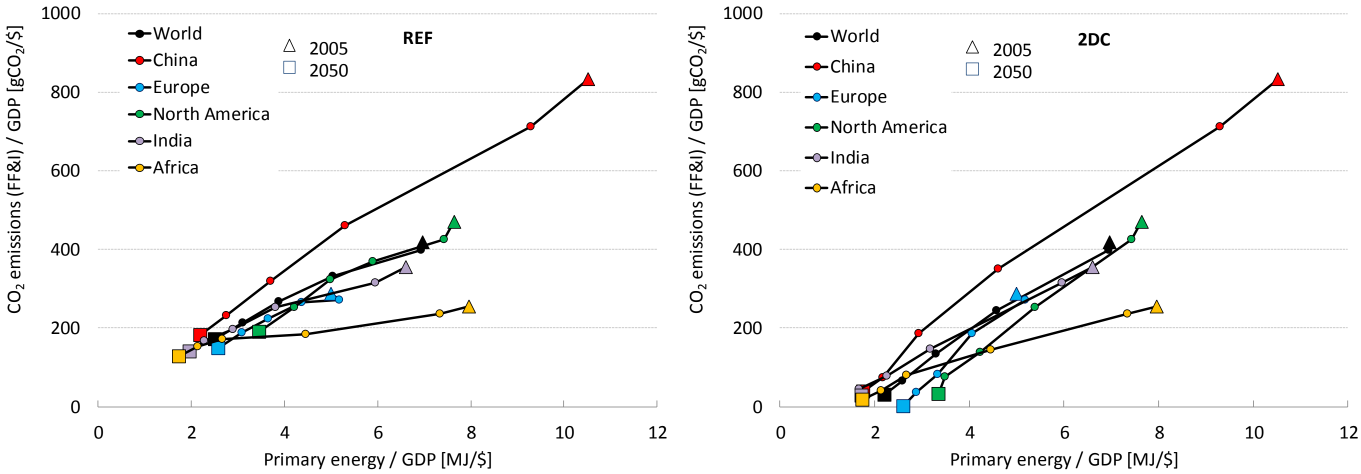

Figure 14. CO_2 emission intensity against primary energy intensity, per unit of GDP, for five major economies, and global values, under the REF (left) and 2DC (right) scenarios.

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