

An integrated assessment of pathways for low-carbon development in Africa

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ABSTRACT

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, even given high GDP and population growth: we find figures that are close to half this level. On the other hand, we find evidence for leap-frogging opportunities, by which renewable energy options rather than fossil fuels could constitute the cost-optimal solution to fulfil most of Africa's growing energy requirements. An important benefit of leap-frogging is that it avoids an ultimately expensive fossil fuels lock-in that would fix the carbon footprint of the continent until at least the middle of the century.

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 to achieve deep cuts in greenhouse gas (GHG) emissions (for the latest editions, see IPCC, 2011, 2014). Integrated Assessment Models (IAMs) constitute an important tool of analysis in the studies reviewed in these publications. In recent years increasing attention has been paid by research groups across the world that operate these models 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 limited, 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 (UN, 2014), 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

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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 large, 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 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 “leap-frogging” the use of fossil fuels, that is, launching energy systems that from the outset mostly rely on renewable forms of energy, rather than following the pathways of developed countries that since the industrial revolution built their economies with coal, oil and natural gas as predominant energy resources. 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 can 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 how to provide “sustainable energy for all”, by assessing the energy requirements associated with this goal in Africa (UN, 2012). By focusing on the use of renewables and some of its ramifications in Africa we also briefly touch upon an important aspect of the water-energy-food nexus (IRENA, 2015): the possible water and food (price) implications of traditional and modern biomass-based renewable energy. 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 in which more details can be found describing it. 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 subsections 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 energy systems models based on the TIMES software platform and is described in detail in Loulou and Labriet (2008) and Loulou (2008). As bottom-up model it is characterized by achieving a partial equilibrium in which energy production meets an essentially exogenously determined demand for energy services, unlike top-down models that calculate endogenously a general equilibrium between supply and demand (see, for example, van der Zwaan et al., 2002). 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. 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 of energy demand and corresponding cost variations are thus 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 (electricity generation, industry, residences and commerce, transport), 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 Fig. 1 and Lvan der Laan, 2015). 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 inspecting in greater detail the energy systems of individual regions within Africa. 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

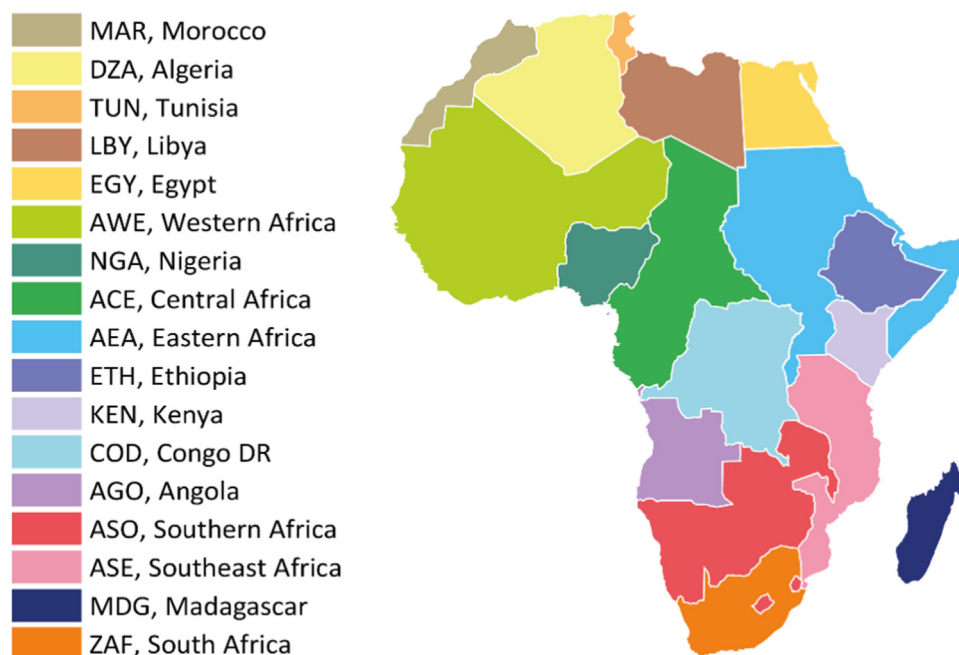


Fig. 1. TIAM-ECN's geographical disaggregation of Africa in 17 regions.

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.

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 Fig. 2 for a schematic diagram). TIAM-ECN allows for performing cost-based analysis under multiple scenarios – for the purpose of the present study we run four of them. 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 2 °C. For this scenario we assume that the additional (anthropogenic) atmospheric radiative forcing does not exceed

2.6 W/m² (RCP2.6; see IPCC, 2014). The third one is a climate policy scenario in which we assume that a global carbon market is established with a CO₂ price increasing with a rate of 4%/yr from 50 US\$/tCO₂e in 2020 to over 160 US\$/tCO₂e 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).

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 of the hundreds of technologies 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 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 notably Loulou (2008), Loulou and Labriet (2008), van der Zwaan et al. (2013a), Kober et al. (2014), and van der Laan (2015).

Fig. 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 Fig. 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

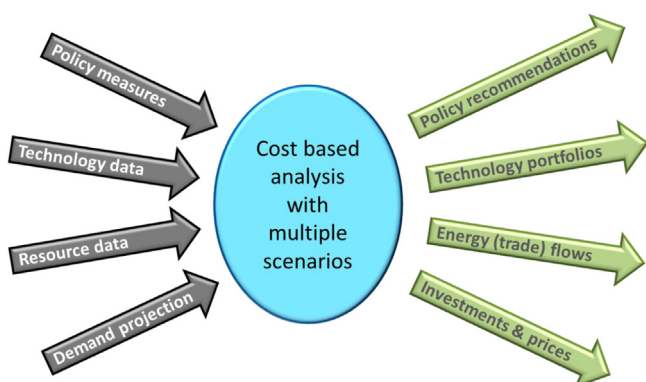


Fig. 2. Stylistic representation of the main inputs and outputs of TIAM-ECN.

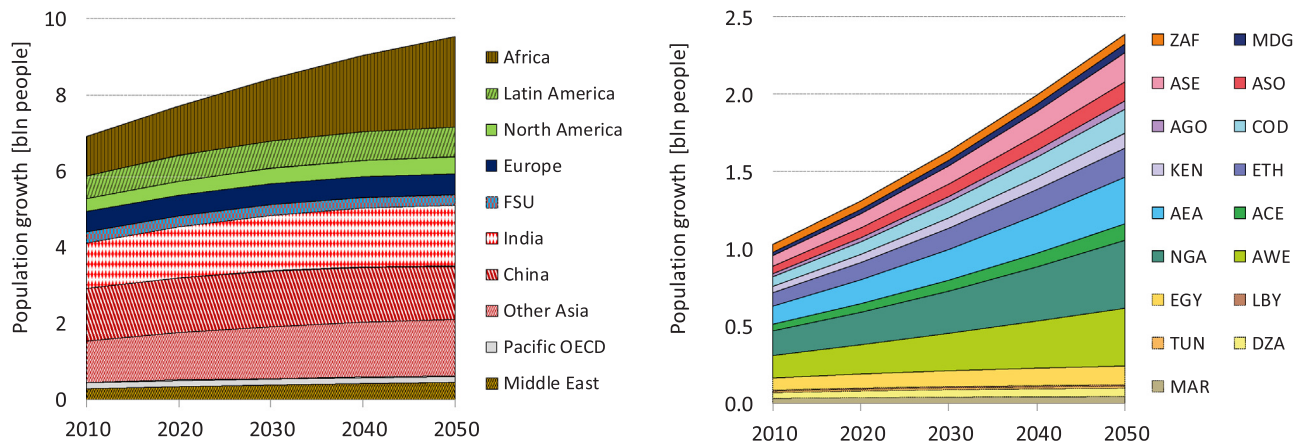


Fig. 3. Population growth for the major economies in the world (left) and demographic breakdown for the 17 regions in Africa (right) as simulated in TIAM-ECN.

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 6-fold over the time frame of our scenario runs. Given the expected doubling of the population on the continent, GDP per capita ‘only’ increases 3-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

Fig. 4 (left plot) show that global GHG emissions (including CO₂, CH₄, and N₂O, but excluding other GHGs) in the REF scenario increase steadily from their 2015 level of approximately 50 GtCO₂e (GtCO₂-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 more than world-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 30–40%, 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.

In Fig. 5 we see for Africa the same type of information (i.e. GHG emission developments) as depicted in Fig. 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 Fig. 5, CO₂ emissions can more easily be reduced as a result of climate policy under our cost-minimisation structure than emissions of CH₄ and N₂O. The explanation is that in e.g. the power sector more means exist to abate GHG emissions than in agriculture, and abatement costs for CH₄ and N₂O emissions in the latter are relatively high in comparison to CO₂ emissions abatement costs for electricity generation. Note that this graph is expressed in GtCO₂e terms: in volume terms CH₄ and N₂O are emitted one to two orders of magnitude less than CO₂. If one compares the emission levels of CH₄ and N₂O between 2010 and 2050, an increase can be

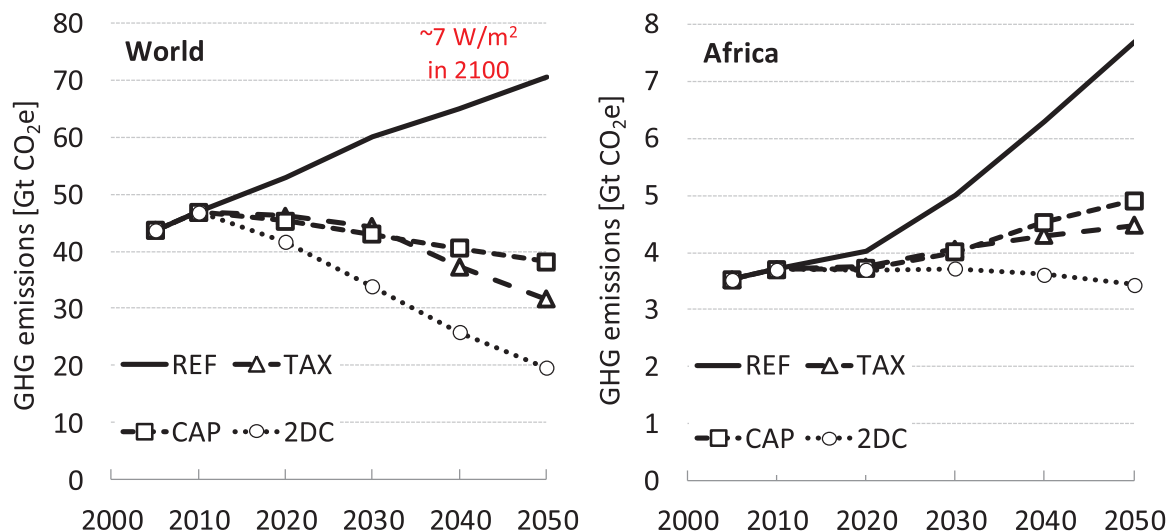


Fig. 4. GHG emissions in the world (left) and Africa (right) in our four scenarios.

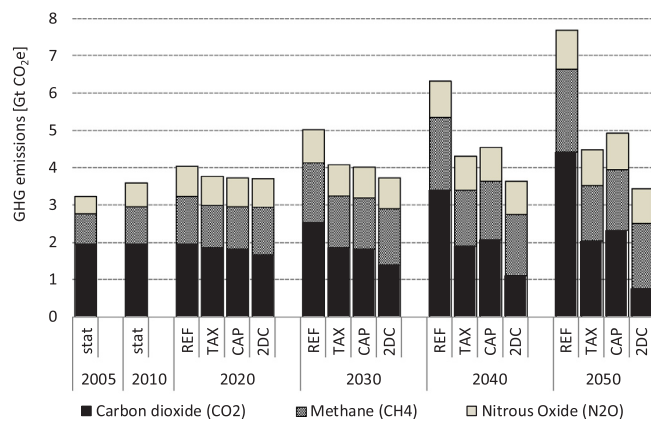


Fig. 5. Breakdown of GHG emissions in Africa in our four scenarios.

observed for both these gases independent of the scenario considered. This does not imply, however, that agriculture (from which most CH₄ and N₂O 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 CH₄ and N₂O emission terms, the mitigating effects of agro-technological progress. An insight from Fig. 5 is that in a reference scenario the largest contribution to climate change in Africa until 2050 continues to derive from CO₂, while under climate change control policy the relative weight of CO₂ gradually decreases. Under a 2DC scenario, the situation reverses: CH₄ and N₂O combined yield in 2050 the majority of Africa's climate change footprint. In the Online Appendix we show how the CO₂, CH₄, and N₂O emission intensities per capita (and their evolution over time) compare to their world average equivalences.

Fig. 6 zooms in on the evolution of CO₂ 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 CO₂ in industry continue to play a role in all scenarios until 2050, although in the 2DC scenario its contribution becomes negligibly small from about 2040. Emissions of CO₂ from the residential sector rise despite climate policy, except in scenario 2DC, where it becomes essentially carbon-free in 2050. Emissions of CO₂ in the commercial and upstream sectors, as well as in agriculture, remain very small throughout this time frame, but large CO₂ emission changes take place in land-use and transportation. Land-use CO₂ emissions are substantially curtailed in all cases, including the reference scenario (mostly

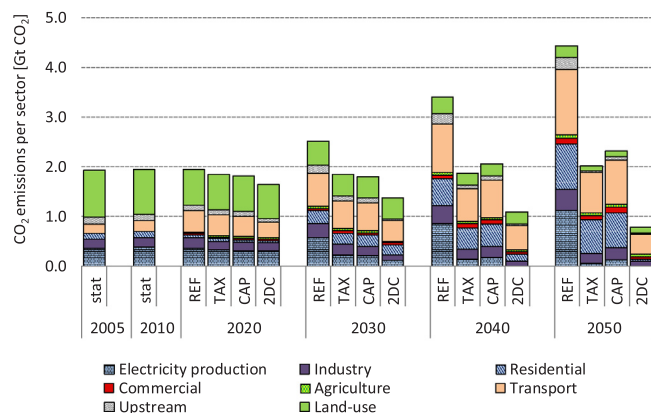


Fig. 6. Sectoral breakdown of CO₂ emissions in Africa under our four scenarios.

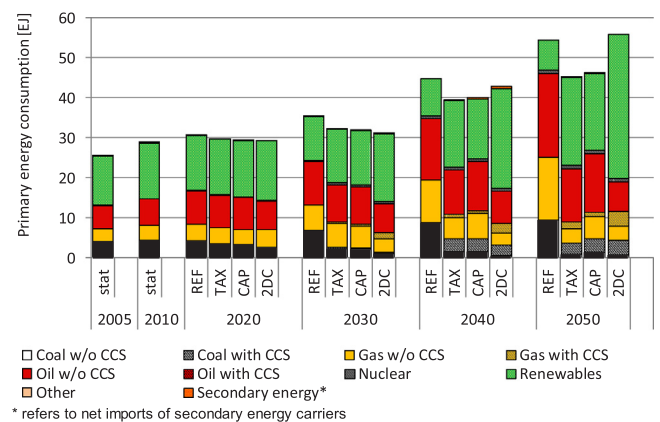


Fig. 7. Primary energy consumption with resource breakdown in Africa in our four scenarios.

based on arguments of environmental protection). Emissions of CO₂ in the transport sector increase over the forthcoming decades in all scenarios, even in 2DC.

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 is also realised in areas where abatement technology is usually quite costly, such as in industry. Only in the 2DC scenario CO₂ emissions in 2050 are below those today, by more than a factor of two. Yet the structure of these emissions is fundamentally different: while about half of all CO₂ emissions in 2010 derived from land-use, in 2050 transportation accounts for about half.

Fossil fuels – at the origin of an important share of Africa's CO₂ emissions – play a large role in its overall energy supply, and are likely to do so under all scenarios that we investigated. This is demonstrated in Fig. 7, in which all main energy resource types are depicted that contribute to total primary energy consumption on the African continent. As can be seen, today renewables account for about half of primary energy usage, mostly in the form of biomass.

Fig. 8 depicts the TIAM-ECN results for the intensity per capita of CO₂ 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.

As one can see from Fig. 8, the dynamics under the REF scenario (left plot) generally plays out along the diagonal, implying a coupling between energy and CO₂: in North America both CO₂ 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 significantly drops, under an almost constant CO₂ intensity, while from 2020 to 2050 the CO₂ 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 CO₂ 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 CO₂ emissions intensity from 2020 onwards.

In the 2DC scenario (right plot of Fig. 8) we see that all lines towards 2050 point downwards as a result of the stringent climate policy that

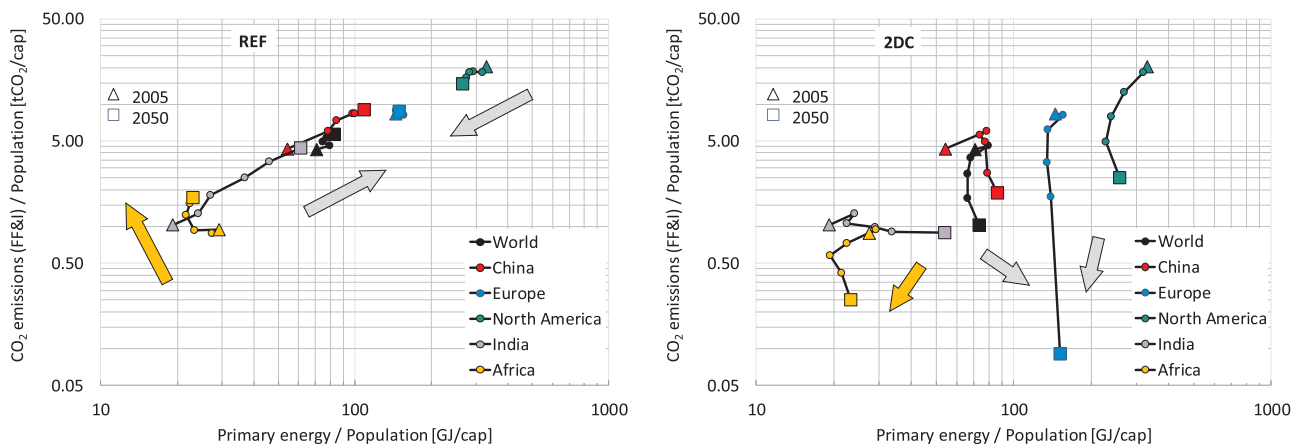


Fig. 8. CO₂ emission intensity against primary energy intensity for five major economies, and their global values, under the REF (left) and 2DC (right) scenarios.

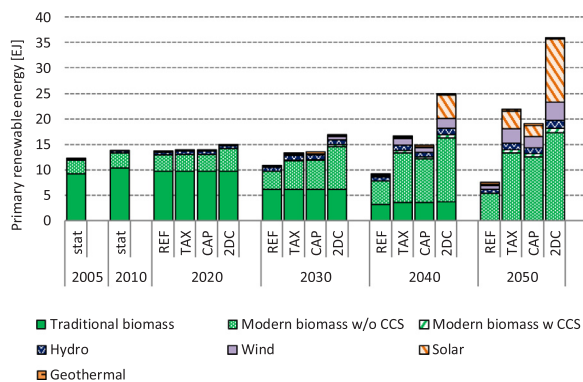


Fig. 9. Primary renewable energy use in Africa under our four scenarios.

complies with the Paris Agreement goal of staying within a temperature increase limit of 2 °C. For Europe and North America (as well as for the world as a whole) we see substantial improvements in CO₂ intensity under relatively constant energy intensity values. For China we see until 2020 an increase of both the energy intensity and CO₂ intensity, while from 2020 onwards mostly a substantial drop in CO₂ intensity (under a quite stable energy intensity). For India one observes on average an almost unchanging level of CO₂ 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 CO₂ 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 nearly have been completed by 2050, but will play out during the latter half of the century, when incomes will rise and eventually per-capita energy consumption will grow from 20 to 30 GJ/capita where it stalls 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, even as GDP and total energy use grow substantially, moderates per capita increases in both these parameters. Although Africa's gradual development over the next decades materializes at a tenfold lower per capita emissions level and energy use 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 Fig. 8, resembles that of the transition the developed regions in the world are projected to go through, more so than the way currently China and India develop. This may be an indication for potential leap-frogging over a carbon-intensive 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 the average for Africa our findings stand out quite clearly.

Note that the fact that the CO₂ 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 CO₂ intensity. In the case of the US, however, it is at a higher starting level than for Europe. The US decreases its CO₂ 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 [Online Appendix \(Fig. 14\)](#) we show similar plots as the two depicted in Fig. 8, but with the denominator 'per capita' replaced by 'per unit of GDP'.

Fig. 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.

For the climate change control scenarios, on the other hand, we see that the use of renewables strongly increases, 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. In the 2DC scenario notably solar power becomes an essential part of the African energy system. We also observe an enhanced hydro-electricity generation, 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.

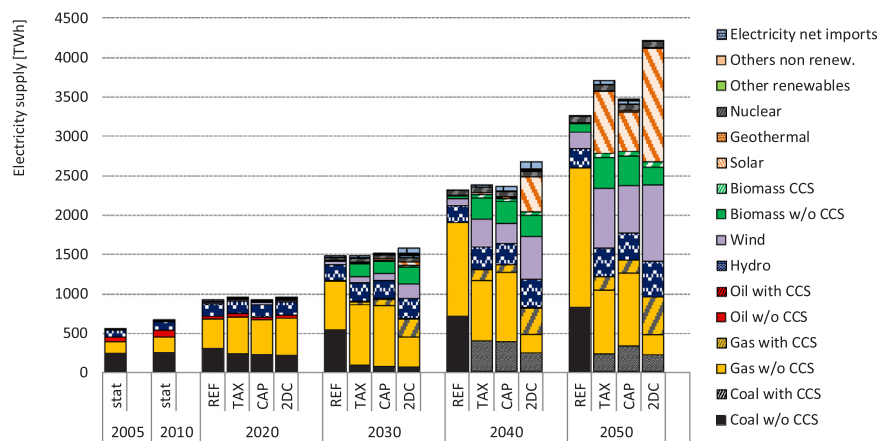


Fig. 10. Electricity supply in Africa under our four scenarios.

How electricity demand in Africa, and correspondingly supply, increments exponentially under each of our four scenarios is plotted in Fig. 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. In addition, we see a gradually 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.

The medium-term (2030–2050) prospects for power capacity additions constitute an indicator for required public and private activities in the electricity sector. These are reported, expressed as annual averages in GW/yr, under the 2DC scenario, in Fig. 11. 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 rates for options like natural gas, wind and solar energy based electricity generation 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. Fig. 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.

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, Fig. 11 shows that even in a scenario where per-capita energy use does not rise, the investments to modernize energy usage in Africa (through electrification) 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 leap-frogging towards renewable energy systems in support of their low-emission development strategies (AREI, 2015). In this article we report evidence for the feasibility of leap-frogging from an energy-system cost minimisation perspective. Our analysis of multiple scenarios reveals that it is optimal to preclude the use of CO₂-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 spontaneously. We conclude, however, that AREI's target of an additional 300 GW of renewable power production capacity by 2030 is

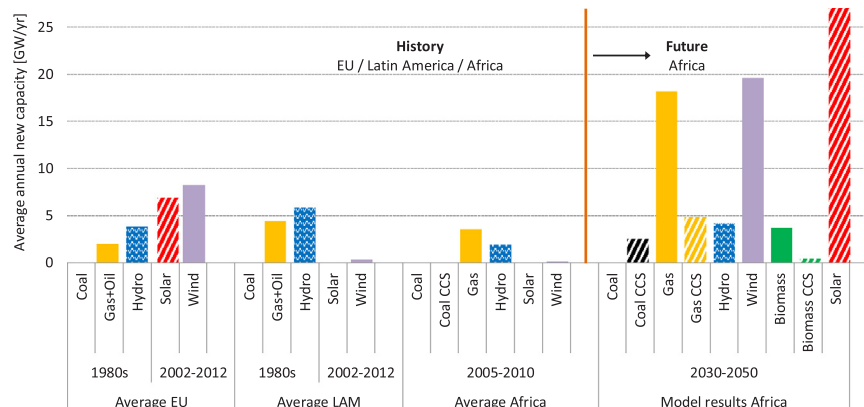


Fig. 11. Electric power capacity additions: past for Africa, EU and Latin America, and prospects for Africa under the 2DC scenario.

probably unrealistic. Even in our most ambitious scenario (2DC), at most about half of this figure is reached.

Today, Africa contributes less than 8% to global emissions of approximately 50 GtCO₂e for the three most important GHGs (CO₂, CH₄, and N₂O). 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 2 °C, 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 becomes 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. Similarly, we 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 has been updated to better represent the African energy system and regional population and economic growth projection divergences. For the work by Lucas et al. (2015) an existing database with previously established model runs was used, generated in the LIMITS project (2011–2014), for which no African energy system simulation improvement was undertaken. The level of spatial disaggregation of Africa in TIAM-ECN hopefully sets a new benchmark for studies dedicated to the continent relative to, for example, the World Energy Outlook model of the IEA (IEA-WEO, 2014). We agree with Lucas et al. (2015) that renewable energy options possess great deployment potential. Our current results disagree, however, with their finding that CO₂ 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.

As in Latin America, Africa's non-CO₂ emissions contribute substantially more to the overall GHG balance than in other parts of the world. At present, close to 40% of GHG emissions in Africa and Latin America – expressed in GtCO₂e – derive from CH₄ and N₂O, 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), CH₄ and N₂O 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 CO₂ emissions can more easily and less expensively be reached than CH₄ and N₂O emission reductions, which results in decreases of the former being realised earlier and more aggressively than for the latter. Today around 1 GtCO₂/yr, half of all CO₂ emissions in Africa, derive from land-use (change). In 2050 we project this to fall to 0.1–0.2 GtCO₂/yr, irrespective of the (reference or climate policy) scenario considered. We underscore the significant role of land-use change in the African emissions context and the continent's important – but diminishing – role as a global carbon sink. Our approach could be useful in linking the role of land-use change to that of the energy sector in a common policy framework, whereby we expand on research dedicated to the carbon balance in Africa (Bombelli et al., 2009; Ciaia et al., 2011; Valentini et al., 2014).

Primary energy consumption in Africa is likely to remain below 30 GJ/cap until 2050, independent 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 tCO₂/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 tCO₂/cap in 2050 in the 2 °C 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 CO₂ emissions than any other region in the world. Technology leap-frogging in a rapidly growing energy system could lead to Africa attaining a carbon intensity of around ¼ of the world average by 2050. This could open up opportunities for Africa as a place to do 'clean' business and manufacturing.

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 traditional carbon-intensive (non-sustainable) ways for e.g. cooking and heating (mostly in solid form, essentially fuel wood and charcoal) is replaced by modern low-carbon (sustainable) usage in many sectors, notably cooking and its combustion in solid (waste) form in thermal power plants. 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, in order to preclude negative externalities in the food and water sectors (in terms of e.g. food prices respectively water availability, as well as the emission of pollutants and use of fertilizers, or biomass harvesting, deforestation and biodiversity).

We find that electricity generation provides a powerful way to mitigate climate change: the African power sector expands 6-fold in 4 decades in our 2DC scenario, that is, more than the close to 5-fold growth that our model generates for the reference case. The associated average annual capacity additions required for options like solar and wind power, as well as natural gas based electricity generation, is in the medium term (2030–2050) 2–3 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). While SDGs are not the main research focus of our article, we find indications that the SDGs may well be mutually compatible. For example, the 2DC scenario allows for strong economic growth (SDG 8), 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 generate the necessary technical and financial expertise. In South Africa, for instance, the Renewable Energy Independent Power Producer Procurement Programme (REIPPP) has been designed for creating PPPs with as goal to diversify the country's generation mix by supplying renewable energy to the grid. The terms of reference of the supply contract bidding process emphasized that projects should offer economic benefits to the communities involved. Thereby, REIPPP could – and actually meanwhile did – achieve the 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 among the lowest costs for renewable electricity production in the world. If other African countries are to follow this example, governments will have to improve on guaranteeing clear, consistent and transparent regulation with regards to renewable on- and off-grid energy deployment. This will stimulate the establishment of an attractive financial environment, which is essential for renewable energy diffusion (Schwerhoff and Sy, 2017; WB, 2017). We think that the family of IAMs to which the TIAM-ECN model belongs need to be substantially improved in order to more accurately reflect financial conditions (Sweerts et al., 2018).

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.enpol.2018.03.017>.

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