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Do Kenya's climate change mitigation ambitions necessitate large-scale renewable energy deployment and dedicated low-carbon energy policy?

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ABSTRACT

In this paper Kenya's climate change mitigation ambitions are analysed from an energy system perspective, with a focus on the role of renewable and other low-carbon energy technologies. At COP-21 in 2015 in Paris, Kenya has committed to a 'nationally determined contribution' of reducing domestic greenhouse gas emissions by 30% in 2030 in comparison to a business-as-usual projection. An efficient exploitation of the country's renewable energy resources is key to achieving this target. We use the TIAM-ECN model to characterize plausible development pathways for the Kenyan energy mix until 2050 under different climate change mitigation scenarios. We conclude that the power sector can expand with mostly renewable energy options even in the absence of stringent greenhouse gas abatement targets. On the contrary, on the demand side a substantial deployment of low-carbon technologies is triggered only when ambitious emission reduction objectives are in place. The introduction of these technologies entails additional energy system costs, ranging in 2050 from 0.5% to 2% of the country's GDP. Our analysis supports the feasibility of Kenyan climate management goals, provided that adequate investments in renewable and other low-carbon energy technologies are timely made available.

1. Introduction

With its Vision 2030 programme, the Kenyan government has set ambitious goals for future economic growth of the nation, aiming at becoming a middle-income country by 2030 [1]. The development of a reliable and climate-resilient energy system plays a central role in the programme, as indicated in the National Climate Change Action Plan – NCCAP [2].

Even though Kenya's contribution to greenhouse gas (GHG) emissions on a global level is small, the country's rapidly growing population and expanding economy could lead to a significant increase in its GHG levels in the future, which would exacerbate climate change. Moreover, Kenya's current energy supply and economy are potentially vulnerable to the adverse effects of global average atmospheric temperature increase, the former being heavily reliant on hydropower, the latter on agriculture and tourism. Consequently, the government of Kenya (GoK) has set ambitious plans for both climate change mitigation and adaptation [2]. Kenya's commitment to low-carbon development has recently been confirmed at the 21st Conference of the Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC) in 2015 in Paris [3]. In its Nationally Determined Contribution (NDC) Kenya has pledged to reduce its GHG emissions by 30% in 2030 in comparison to a business-as-usual projection [4].

Kenya's NDC builds on a baseline projection of 141 $MtCO_2e$ in 2030, i.e. a doubling from 2010 values, as formulated in the country's Second National Communication (SNC) to the UNFCCC [5]. Its NDC thus implies a maximum allowed emission level in 2030 of just below 100 $MtCO_2e$. One of the key elements consistently pursued in Kenya's GHG reduction strategy is to exploit the large renewable energy potential the country is endowed with, in order to substantially expand its low-carbon power sector. Its abundant resources of for instance geothermal, wind and solar energy could be efficiently developed to render the electricity generation mix – traditionally reliant on hydropower and imports of oil products

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[6,7] – more diversified. This trend has already started: the share of geothermal power to overall electricity capacity has increased from 13% in 2011 to 26% in 2015 [8,9]. Hydropower and fossil fuels account for another 36% each. The remaining 2% is evenly divided between wind and cogeneration, with a small contribution of 0.02% from solar PV, for a total of 2.3 GW installed capacity [11].

Current electricity consumption in Kenya amounts to about 30 PJ [7]. The largest share of energy use originates from traditional biomass burning (e.g. wood, charcoal) for cooking in the residential sector (440 PJ). Oil products are mostly used in the transport sector (100 PJ), while about 15 PJ of coal are consumed in the industrial sector [7].

Renewable energy deployment in Kenya, especially in the power sector, is a subject that has been amply described in official national documents as well as studied in depth in the scientific literature. The Kenyan National Environment Management Authority estimates that geothermal energy alone could yield a GHG abatement of as much as 14 $MtCO_2e$ in 2030, while wind and solar energy could deliver about 1.4 and 1.0 $MtCO_2e$ in emissions reduction, respectively, in that year [2]. The country's large domestic wind energy potential has been identified and studied for several decades (see e.g. Ref. [10]), as has the use of solar energy for decentralized electricity production in rural areas (see e.g. Refs. [11,12]). Recent studies have focused on the benefits that low-carbon energy technologies could entail for rural low-income populations [13], on their potential contribution to poverty reduction [14], as well as their overall affordability [15].

The purpose of our paper is threefold. First, we explore the extent to which large-scale renewable energy technology deployment is required to achieve Kenya's GHG abatement ambitions by focusing in particular on the energy demand and power sectors. The second objective of our work is to assess the plausibility of the official business-as-usual (BAU) emissions projection until 2030 as documented by the GoK, as well as the corresponding formal Kenyan NDC trajectory as formulated under the Paris Agreement. Our final goal is to inspect possible long-term climate policy scenarios until 2050 for Kenya, in an attempt to go beyond today's first-step targets that so far have been internationally agreed upon but that will need to be tightened as time proceeds. In section 2 we present a brief review of Kenya's current GHG emission reduction objectives. In section 3 we introduce the TIAM-ECN model that we use for our research, and describe the scenarios analysed in this paper. Section 4 presents the outcomes of our model runs. In section 5 we discuss our results, while we reserve section 6 for our policy recommendations and final conclusions.

2. GHG emissions in Kenya

Kenya's SNC provides an inventory of national GHG emissions over the past decades until 2010, as well as their projections up to 2030 [5]. The latter are reproduced in the left panel of Fig. 1 (solid black line, representing BAU). These projected emissions have been disaggregated into five main categories, for agriculture, energy & power, transportation, industry & waste, and land use, land use change and forestry (LULUCF), respectively, as depicted in this Figure. The energy & power category comprises emissions generated in the residential, commercial and power sectors. These are foreseen to increase the most in absolute terms, from 7 $MtCO_2e$ in 2010 to 50 $MtCO_2e$ in 2030. This is a consequence of the large expansion in both the power sector and the demand for energy services, driven by rapid population and economic growth in Kenya. The contributions from the other categories remain roughly constant or experience a relatively small growth. A total GHG abatement potential of over 85 $MtCO_2e$ in 2030 is calculated in the SNC [5]. The NDC trajectory, set to attain about half of this potential by 2030, is shown as the dashed black line in the left panel of Fig. 1.

Emissions from LULUCF in Kenya are mainly caused by deforestation, for example for charcoal production and the creation of new cropland. There is significant uncertainty in historic LULUCF data, as highlighted in Ref. [4]. The SNC estimate of 21 $MtCO_2e$ emissions from LULUCF in 2010 is over twice as high as the value of 9.4 $MtCO_2e$ reported by the World Resource Institute [16] for the same year. It is even a factor of five higher than the 4 $MtCO_2e$ reported in the EDGAR database [17] for the year 2008. The uncertainty propagates to the projected level of future emissions from LULUCF, as well as to the contribution from this sector to overall GHG abatement in 2030 [5].

Due to the high uncertainty in the role of LULUCF, we decided to exclude this sector from our present analysis, focusing instead on the other sources of GHG emissions, and particularly zooming in on the energy demand and power sectors. The right panel in Fig. 1 presents the same data as in the left panel, but excluding the contribution of LULUCF from both the BAU and the NDC projections (solid and dashed red line, respectively). The pathways depicted in the right panel of Fig. 1 constitute the baseline for comparing and assessing the climate policy scenarios that we consider in the remainder of our paper; the BAU and NDC projections excluding LULUCF will hereafter be labeled *GoK: BAU* and *GoK: NDC*, respectively. Note that the 30% GHG emissions reduction as reported in Kenya's NDC translates in our study, in which we do not consider the GHG emissions contribution (and abatement thereof) from LULUCF, into a GHG emissions reduction of 20%.

3. Methodology

We use the TIAM-ECN model to project least-cost developments of the Kenyan energy system under different climate policy assumptions. TIAM-ECN (the TIMES Integrated Assessment Model, operated at ECN) is a well-established version of the global TIAM model developed under IEA-ETSAP (the IEA Energy Technology Systems Analysis Program), which is an Implementing Agreement organized by the International Energy Agency (IEA) in Paris.

Like with other members of the TIMES family, TIAM is a technology-rich bottom-up energy system model. It is described in detail in Refs. [18,19]. TIAM is a linear optimization model that minimizes energy system costs in each time-period with perfect foresight. The objective function includes capital, operation & maintenance, as well as fuel costs. Decommissioning and energy infrastructure costs are also included, albeit in an approximate way. Demand for energy services responds to changes in their prices through end-use price elasticities. Savings of energy demand are thereby accounted for in the objective function.

TIAM-ECN is built on a database of hundreds of energy-related processes and commodities, which allows for the simulation of the entire global energy system from resource extraction to end use. It is designed to cover a period of over 100 years and hence can be used to generate scenarios for the entire 21st century. For a general description of the reference energy system of TIAM-ECN see also [20]. Over the past years TIAM-ECN has been used successfully for analysis in several different domains, including on topics like developments in the transport sector (see e.g. Ref. [21]), the power sector [22], and burden-sharing among countries for global climate change control [23]. Other examples of studies with TIAM-ECN – that also provide additional descriptions of parts of our model – include work on global and regional technology diffusion (see e.g. Ref. [24]). In the current set-up of TIAM-ECN, the world is disaggregated in 36 distinct regions [25,26]. Kenya is modeled as a separate 'region', enabling the country-level analysis presented in this paper. A detailed description of the input parameters for Kenya, as well as the rest of Africa, can be found in

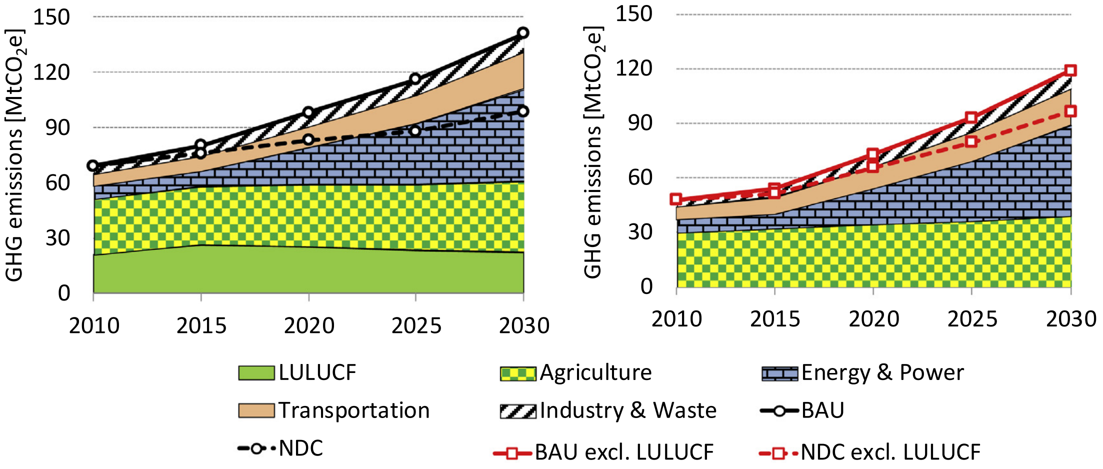

Fig. 1. GHG emissions in Kenya, according to its SNC projections, including (left panel) and excluding (right panel) contributions from land use, land use change and forestry.

Ref. [25].

TIAM-ECN simulates the three most important types of greenhouse gases – carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) – while other GHGs (that, even if combined, contribute little to global climate change) are not accounted for. In the remainder of this paper, the acronym GHG refers to these three gases only. Emissions related to energy conversion processes are modeled endogenously, while for those originating from several other activities, such as e.g. agriculture, exogenous reference profiles are used. The model includes abatement options for all origins of emissions, i.e. for both energy- and non-energy related sources. For the former many low-carbon technology alternatives are available, while for the latter cost-potential curves for GHG mitigation measures are simulated.

In this paper TIAM-ECN is used to analyze four pathways for the possible development of the Kenyan energy system. These correspond to four distinct scenarios, which represent different degrees of GHG emissions abatement ambition, on a global as well as continental and national level (for Africa and Kenya, respectively):

Reference (REF) No GHG emission reduction or renewable energy deployment policies are enacted or proposed after 2010.
High carbon price (TAX) A global carbon market exists with exogenously assigned CO_2 prices, increasing from 50 US$/t$CO_2$e in 2020 to 162 US$/tCO_2e in 2050.
Paris commitment (NDC) A 20% emission reduction is achieved in Kenya in 2030 (in comparison to the REF scenario, without considering LULUCF). The maximum allowed emissions level is kept constant in subsequent years until 2050. In the rest of the world a cap-and-trade system is in place with a global target for 2050 to reduce GHG emissions by 20% in comparison to 2010.
Carbon cap (CAP) A cap-and-trade system is in place with a target to reduce global GHG emissions in 2050 by 30% in comparison to 2010; CO_2 prices are thus determined endogenously, and the target is also achieved separately in Africa.

We have listed these four scenarios in order of increasing climate change control stringency, for Kenya at least. In other words, the long-term emission reduction targets reached in 2050 become more ambitious from TAX via NDC to CAP. Indeed, as we found out, TAX, NDC and CAP can be thought of as low, moderate and high ambition climate management scenarios, respectively, in terms of depth of GHG emission cuts. We explore this stringency in more detail in the following section.

TIAM-ECN's start-year is 2005, while its 'projections' for 2010 are used to calibrate the model against statistics. TIAM-ECN being a partial equilibrium model, energy demand in the different sectors is projected based on drivers such as population and economic growth, which are exogenous inputs to the model. Data on population and GDP developments are taken from databases of the UN and World Bank (see Refs. [25,27,28,29] and references therein). In all scenarios the assumptions for population and GDP growth in Kenya between 2010 and 2050, are from 41 to 97 million inhabitants and from 91 to 1500 billon US$, respectively.

4. Results

Fig. 2 presents our projections of final energy consumption in Kenya, disaggregated in different classes of energy carriers. Each bar in the chart represents a unique combination of year and scenario run. TIAM-ECN data for 2010 are compared with historic values (bar "stat"), which shows a good match between model projections and statistics for all scenarios. The largest portion of energy consumption in 2010 originates from biomass, more specifically fuel wood and charcoal burning for cooking in the residential sector. Oil products are the other main energy carrier. These are consumed primarily in the transport sector (70%), but are also used in the residential sector (again for cooking, 10%) and in the industry (20%). Biomass and (imported) oil products are projected to remain the main source of energy until at least 2030. In subsequent periods, a differentiation across scenarios can be observed in the energy mix. Without the introduction of GHG emission reduction policies (REF scenario), energy consumption will mainly rely on fossil fuels – mostly coal and oil products – with relatively small contributions from biomass and electricity. In climate control scenarios, with progressively more ambitious emission reduction targets, overall energy consumption levels decrease as a result of the deployment of higher efficiency technologies. The energy mix also becomes gradually less reliant on fossil fuels, in favour of biomass, electricity and heat, with a small role for hydrogen in the more stringent scenarios. Our results also highlight the potential exploitation of geothermal energy as a source of heat, besides its already established use in electricity production.

In Fig. 3 the same data are shown, but split by sector rather than fuel type. As can be seen, the largest use of energy takes place in the transport and residential sectors throughout our modelling time frame. The former currently provides a relatively small contribution to energy consumption but is projected to gain in both absolute and

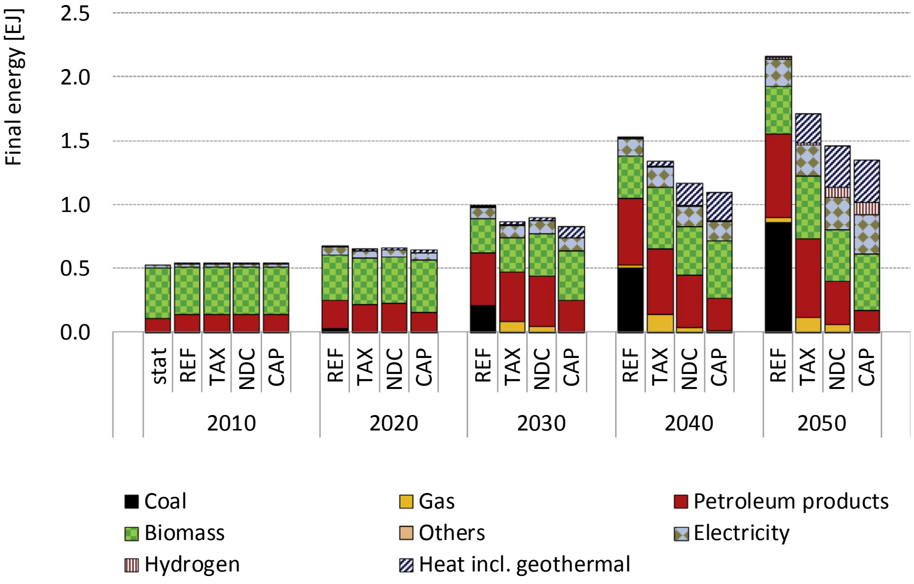

Fig. 2. Final energy consumption projections per carrier in Kenya until 2050, for each TIAM-ECN scenario run.

relative terms already in the near future. The driver behind this growth is an increasing demand for aviation, passenger cars and trucks. We find that fossil fuels dominate the transport sector until 2030 in all scenarios. In subsequent time periods they are progressively replaced by biofuels, and to some extent by electricity and hydrogen. The penetration of alternative (non-fossil) fuels in the energy carrier mix in 2050 ranges from 40% in the REF scenario to 80% in the most stringent CAP scenario. In the residential sector, the largest energy use derives from cooking. Biomass burning in traditional stoves is projected to remain the mainstream way of fulfilling this demand until 2030. After that a shift occurs toward more efficient technologies: coal stoves in the REF scenario and a mix of modern cookers, based on natural gas, biomass or solar energy, in the other scenarios. The growth of energy consumption in both transportation and the residential sector is negatively correlated with the stringency of the emission reduction target. This highlights the realisation of a shift towards technologies that are not only less carbon-intensive, but also more efficient.

In Fig. 2 one observes a progressively larger share of electricity in the energy mix in the long-term. Fig. 4 shows the enlargement of the installed power production capacity required on the supply side to meet this increasing share. The data depicted in Fig. 4 are disaggregated in several technology classes. Hydropower and (imported) oil products represent currently the main sources of electricity generation, while geothermal and coal rapidly gain a substantial share in the mix already by 2020 (see inset in Fig. 4). The 1 GW coal capacity operational from 2020 is supplied by the Lamu power plant, which is currently under construction. This is projected to remain active at least until 2040 in all scenarios. In the REF scenario capacities of 2.0 and 1.5 GW for hydropower and geothermal, respectively, are deployed in 2030. Whereas the hydropower capacity in 2030 is nearly the same across scenarios,

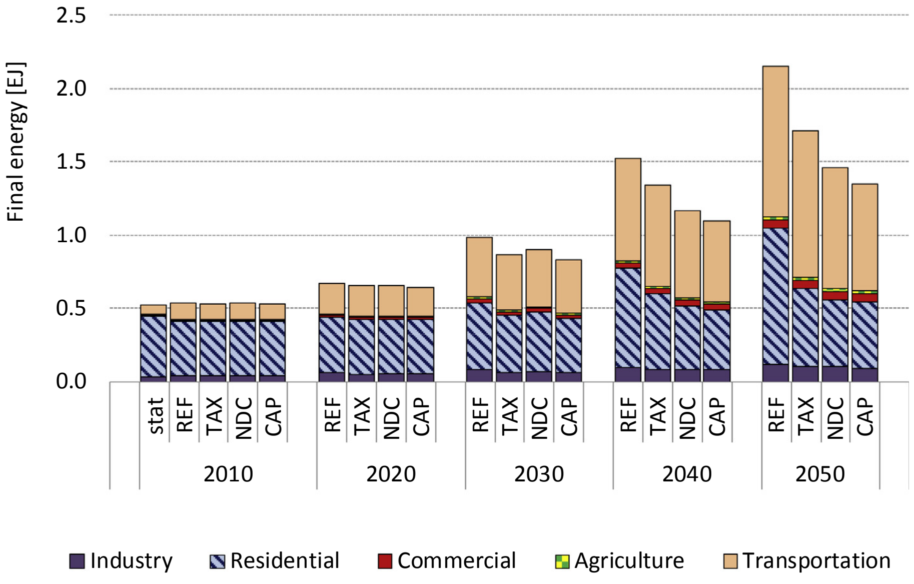

Fig. 3. Final energy consumption projections per sector in Kenya until 2050, for each TIAM-ECN scenario run.

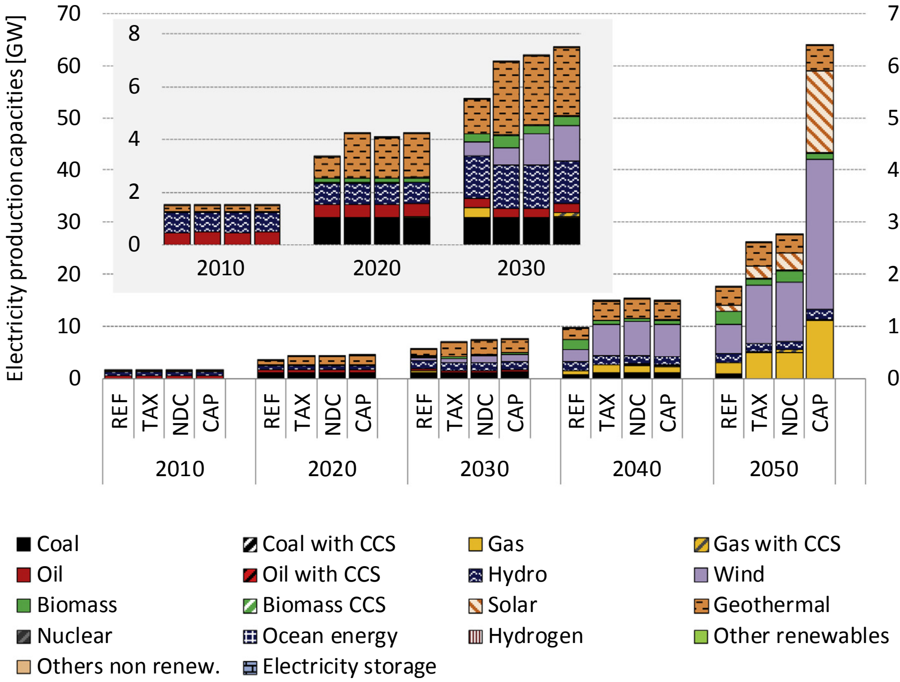

Fig. 4. Electricity production capacity projections per technology until 2050, for each TIAM-ECN scenario run. Inset: zoom-in on the capacity mix until 2030.

geothermal capacity varies from about 1.5 to 3.0 GW, with the highest value in the TAX scenario. Wind energy starts to provide a substantial contribution from 2030, while small roles are reserved for biomass and natural gas based power plants.

The main panel of Fig. 4 demonstrates that towards 2050 the electricity mix is largely dominated by renewables, even in the REF scenario. Wind and geothermal energy, and for the CAP scenario also solar energy, become the main power production technologies. The relatively small contribution from coal in the REF scenario disappears entirely in the climate control scenarios, while in the REF scenario coal is still used for electricity production even beyond 2050. Natural gas based electricity generation is projected to become an important means to compensate for the intermittency of renewable forms of power production and provide peak load capacity. While other technologies (e.g. batteries) are available in the TIAM-ECN database for the same purpose, natural gas results as the cheapest option for Kenya in the model outcomes. As can be seen in Fig. 4, the total installed capacity in 2050 varies greatly across scenarios, from a little below 20 GW in REF to nearly 30 GW in TAX and NDC, and up to as much as approximately 65 GW in the CAP scenario. In the latter most stringent climate change mitigation scenario solar energy reaches a capacity of about 15 GW by the middle of the century.

In our REF projection the installed capacity of electricity production facilities in 2030 totals to about 6 GW (Fig. 4). This is significantly lower in comparison to the 12 GW projected in the SNC BAU scenario, and to the 20 GW of the Low Cost Power Development Plan (LCPDP) of the GoK [6]. The main differences are in the deployment of fossil-fuel-based generation (gas, diesel and coal), geothermal electricity as well as wind energy, which are much lower in the TIAM-ECN projections. The SNC and LCPDP projections differ by the presence of nuclear energy (3 GW) and a higher geothermal capacity (5 GW) in the latter.

Fig. 5 shows our projections for total emissions of all three GHG species. In 2030 the TAX and NDC scenarios achieve a 20% reduction in comparison to the REF scenario, which for both cases meets the target set in Kenya's NDC. We project a 40% decrease in GHG levels for the same year in the CAP scenario, which is twice as large as what is currently targeted. Beyond 2030 the emission trajectories for different scenarios further diverge, reaching values that in 2050 range between 74 MtCO$_2$e and 208 MtCO$_2$e in the CAP and REF scenarios, respectively. While a large reduction in CO$_2$ levels can be achieved by 2050, provided that adequate climate policies are in place, our model projections indicate that it is harder to substantially lower emissions of the other two main GHGs, CH$_4$ and N$_2$O. Comparing the 2050 bars in the figure, while reductions with respect to REF are apparent for CO$_2$ (65%–92%), they are hardly visible for CH$_4$ and N$_2$O (3%–6% and 4%–9%, respectively).

CH$_4$ and N$_2$O emissions originate primarily from agricultural activity and from waste. Several mitigation options are currently available in our model to reduce these non-CO$_2$ emissions, such as related to improvements in the use fertilizers and in waste management. The increase in demand for agricultural products, as a result of population and economic growth, is however so large that it overcompensates the mitigation effects of these options. While a net CH$_4$ and N$_2$O abatement is achieved in each time period when climate control policies are in place, these GHG emissions increase steadily over time in all scenarios in Fig. 5. We observe similar trends in most other regions in Africa as well (see Ref. [30], for additional insights).

The bar chart in Fig. 6 presents sectoral contributions to CO$_2$ emissions projections. In the REF scenario, a rapid increase can be observed from 8 MtCO$_2$ in 2010 to 140 MtCO$_2$ in 2050. This increment mainly takes place in the residential and transport sectors, and is a direct consequence of population and economic growth in absence of GHG abatement targets. The projections for the other scenarios highlight that increasingly stringent climate policies induce a substantial reduction in CO$_2$ levels, starting in the residential sector and followed by the transport sector. In the CAP scenario, CO$_2$ emissions in 2050 amount to 10 Mt – almost as low as the 2010 value.

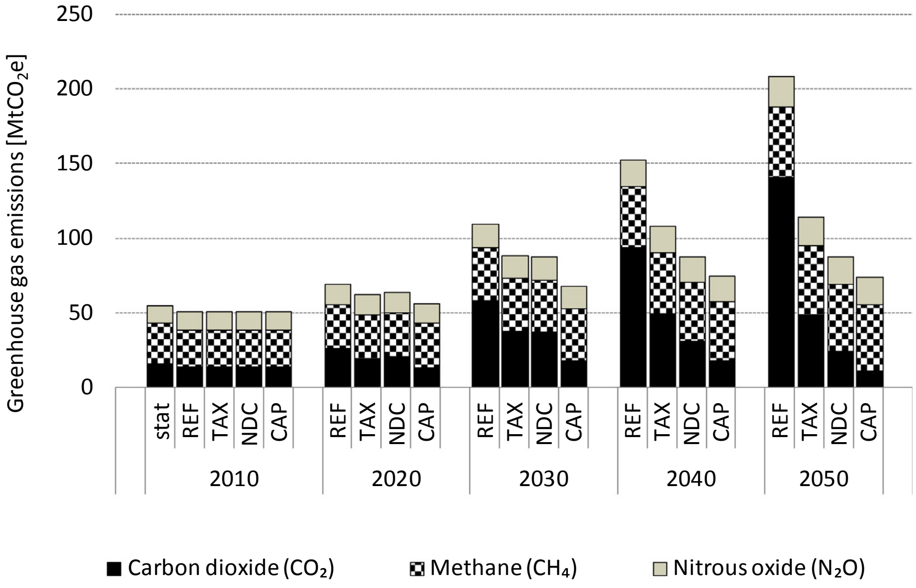

Fig. 5. Emission projections per GHG species, for each TIAM-ECN scenario run until 2050.

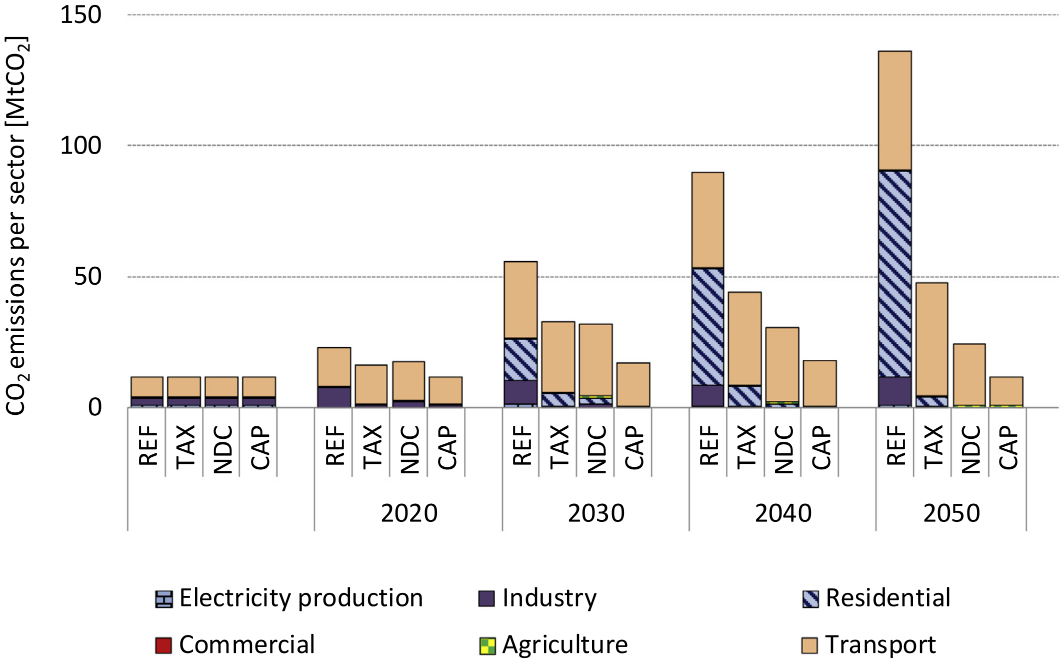

Fig. 6. CO$_2$ emission projections per sector until 2050 for each TIAM-ECN scenario run.

5. Discussion

Renewables contribute significantly to the development of the power sector in Kenya, reaching a share in total electricity production of roughly 80% in 2050 in all scenarios that we investigated (see Fig. 4). This suggests that a low-carbon power sector can be built until the middle of the century, even under substantial population and economic growth projections. As our REF scenario run shows, this can be done cost-efficiently even in the absence of specific climate change mitigation targets. A challenge in this respect is whether an extensive deployment of wind and geothermal power generation capacity is realistic for Kenya from an economic point of view, given the specific cost structure of these options: both are characterised by high upfront investment costs relative to those of their fossil-based counterparts. A stable financial climate is crucial to stimulate entrepreneurship, keep costs down, and enable investments in ambitious renewable energy projects in the power sector. A recent study determined that among a broad range of options wind and geothermal energy possess the highest potential for offering low-cost electricity and a profitable return on investments [15]. This finding is consistent with the projections we show in Fig. 4, in which these two technologies play a prominent role from 2030 onwards in all scenarios, whereas a large-scale deployment of solar energy is only achieved in 2050 in the CAP scenario as a result of its higher costs.

The large presence of intermittent sources in 2050, especially under the most stringent climate mitigation ambitions, poses challenges with regard to building and transforming the required electricity infrastructure. It necessitates timely investments in the development, adaptation and reinforcement of the grid, which should be designed so as to enable the management of variable renewable energy sources. Network upgrades may not only be needed within Kenya's national territory, but long-distance transboundary interconnections might help lowering overall system costs. In fact, regional interconnections support a better exploitation of renewable energy resources across the whole of Africa [31]. Mini-grids may prove essential for the electrification of rural areas [11,12]. Demand for off-grid electricity is represented in TIAM-ECN, but the current level of detail is probably not sufficient to capture all nuances that exist in this domain – work is in progress to improve this part of the model, on the basis of which we intend to more elaborately investigate the potential role of mini-grids in Kenya and elsewhere (for an initial exploration, see Ref. [32]).

As observed in the previous section, in 2030 the level of installed electricity production capacity according to the TIAM-ECN REF projections is significantly lower than that in the SNC and LCPDP projections. These are themselves almost a factor of two apart. The differences in the various estimates are due to diverging assumptions on the growth of electricity demand in the coming decades, and reflect the inherently high uncertainty thereof. A higher degree of electrification would mostly exacerbate the challenge of readily making sufficient capital available for investments in power production capacity and grid expansion.

On the demand side, the largest energy use originates from the residential and the transport sectors (as pointed out in Fig. 3). These two sectors are correspondingly responsible for most of the CO_2 emissions (see Fig. 6). They consequently also offer the highest long-term CO_2 abatement potential, as one can observe by comparing the 2050 projections in Fig. 5 across scenarios. In our model input data, we assume that the traditional use of wood and charcoal for cooking is mostly phased out by 2050, due to its negative impact on air quality, and to the issues it entails with regard to sustainability. In absence of climate control policies, coal stoves are the cheapest replacement for wood and charcoal burning for food preparation, and their pervasive use is responsible for the increase in emissions observed in the residential sector in the REF scenario (see Fig. 6). In all other scenarios, where current forms of cooking are substituted by cleaner technologies, such as natural gas, electric, modern biomass and solar stoves, CO_2 levels in the residential sector are much lower. Similar considerations hold for the transport sector, where the decrease in emissions associated with the most stringent climate policy scenarios correlates positively with the increasing share of alternative fuels, biofuels in particular (e.g. bioethanol and Fisher-Tropsch biodiesel).

Fig. 7 presents a comparison between projections from the *GoK: BAU* and the TIAM-ECN REF scenarios. The 2010 values are in good agreement, even while the TIAM-ECN data are model outcomes and the GoK data represent national statistics. In 2030 the GoK and TIAM-ECN emissions amount to a total of 119 and 109 $MtCO_2e$, respectively. While the overall difference is relatively small, there is a significant deviation in the projections for especially the transport sector (17 $MtCO_2e$ in the GoK baseline vs. 30 $MtCO_2e$ in TIAM-ECN) and the energy & power category (50 and 34 $MtCO_2e$ in the GoK baseline and TIAM-ECN, respectively). The discrepancies are likely due to divergent demand projections in the underlying sectors. This might, in turn, be the consequence of different assumptions on population and economic growth. TIAM-ECN not completely capturing all dynamics of electrification in rural areas may also contribute hereto.

Total GHG emissions in the GoK baseline are about 10% higher than those in the TIAM-ECN REF scenario in 2030, so that the application of the 20% NDC reduction target results in different abatement levels in absolute terms. This is clearly visible in Fig. 8, which presents a comparison between the GoK and the TIAM-ECN emission projections (red and black lines, respectively) across all scenarios considered in this paper. The results suggest that the NDC target is plausible from an energy system and cost-optimality perspective. The official Kenyan projections, however, imply a less stringent maximum allowed GHG level in 2030, in comparison to that calculated under the TIAM-ECN TAX, NDC and CAP scenarios. Fig. 8 points out that the NDC objective can be achieved not only by enacting a national target (as in the NDC scenario), but also through the participation in a global carbon market with relatively high carbon prices (TAX scenario). Furthermore, our results indicate that twice as deep emission reduction levels can be achieved under even more stringent climate policy (such as in the CAP scenario). This finding is in agreement with Kenya's analysis of maximum abatement potentials as presented in its SNC [5]. Fig. 8 also depicts how our scenario projections for 2030 extend until 2050. The large gap between the end points of the REF and TAX lines emphasizes the importance of even relatively unambitious climate mitigation policies in order to keep overall GHG levels under control.

In our model, emission increases can be halted by the large-scale deployment of low-carbon technologies. But the diffusion of these technologies comes with a price tag in comparison to energy system costs incurred in the REF scenario. Fig. 9 shows the total additional annual energy system costs in Kenya required for our three climate policy scenarios from 2010 to 2050, expressed as change in billion US$ relative to the REF scenario. The increasing cost trends observed in the climate scenarios are caused mainly by grid expansion investments, deployment of high-efficiency technologies on the demand side, and fuel switching in the transport sector, rather than by increases in generation costs (many renewable energy technologies are in fact already competitive in the market and further cost reductions are expected). In 2030, there is hardly any change in system costs for the TAX scenario, while in the NDC and CAP scenarios we project an increase of, respectively, 1.4 and 4.8 billion US$. In cumulative terms, the total additional energy system costs between 2010 and 2030 in the NDC scenario are around 17 billion US$. This figure might seem in line with the total cumulative mitigation costs of 16–22 billion US$ reported in Kenya's SNC [5]. There are, however, at least two important differences between the GoK estimate and ours. First, while TIAM-ECN only reports the costs of deploying low-carbon technologies, i.e. GHG abatement costs, the SNC data also include costs related to general infrastructure and legislative improvements aimed at mitigating the adverse effects of climate change. Second, a full implementation of the GoK mitigation measures would lead (according to the SNC) to twice as high emission reduction levels as those in the NDC scenario. In light of these differences the SNC cumulative cost estimate appears to be low in comparison to that of the TIAM-ECN model. In 2050 the additional total annual system costs range from 5 billion US$ in the TAX scenario, to 16 billion US$ in NDC, up to 27 billion US$ in CAP, corresponding, respectively, to about 0.5%, 1% and 2% of the country's projected GDP. This emphasizes the significance of stable financial markets for enabling investments in low-carbon energy technologies.

A comparison of the scenario projections in Figs. 8 and 9 highlights that the level of long-term GHG abatement ambition can have a profound impact on the timing at which the introduction of low-carbon technologies into the energy system is triggered. A substantial growth in renewable energy investments is projected already by 2020 in the most stringent emissions reduction scenario (CAP), while it is deferred to 2030 and 2040 in the medium-reduction (NDC) and modest-reduction (TAX) scenarios, respectively. An important consequence of delaying the implementation

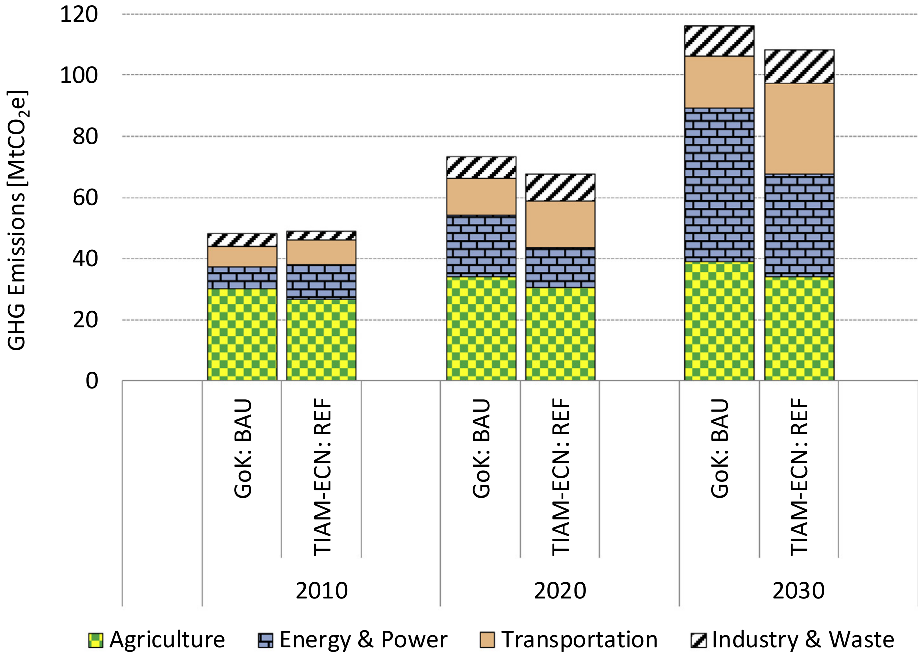

Fig. 7. Comparison of GHG emission projections in the *GoK: BAU* and TIAM-ECN REF scenarios.

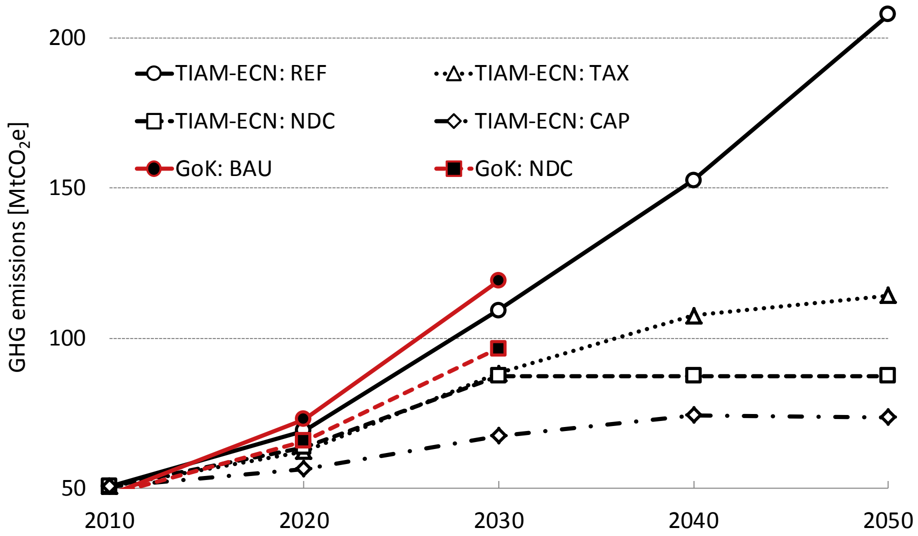

Fig. 8. GHG emission projections for all TIAM-ECN scenarios until 2050, as well as those for the BAU and NDC scenarios developed by the GoK until 2030.

of low-carbon options is that Kenya would have to rely longer on relatively voluminous imports of for instance oil-based products to fulfil its domestic energy demand, and that its large renewable energy resources would remain underexploited.

6. Conclusions and policy recommendations

In this paper Kenya's climate change mitigation ambitions are reviewed and assessed from an energy system perspective. Our main focus is on the contribution of renewable energy to the achievement of its national target of 30% GHG emissions reduction by 2030, relative to a business-as-usual projection. Our results support the feasibility of this objective, provided that sufficient investments in modern low-carbon and high-efficiency technologies are made available. While the establishment of a low-carbon power-sector proves economically attractive even in the absence of stringent climate policies, the latter are essential in order to keep emissions low in the residential and transport sectors. A second objective of our study is the assessment of the plausibility of the official business-as-usual (BAU) emissions projection until 2030 as documented by the GoK, as well as the corresponding formal Kenyan NDC trajectory as formulated under the Paris Agreement. Our results suggest that the NDC target is plausible from an energy system and cost-optimality perspective. The official Kenyan projections, however, imply a less stringent maximum allowed GHG level in 2030, in comparison to that calculated under our TAX, NDC and CAP scenarios. Our last goal is to inspect possible long-term climate policy scenarios until 2050. The long-term projections presented in this paper suggest that even moderately ambitious climate policies, if enacted early enough, can induce relatively large

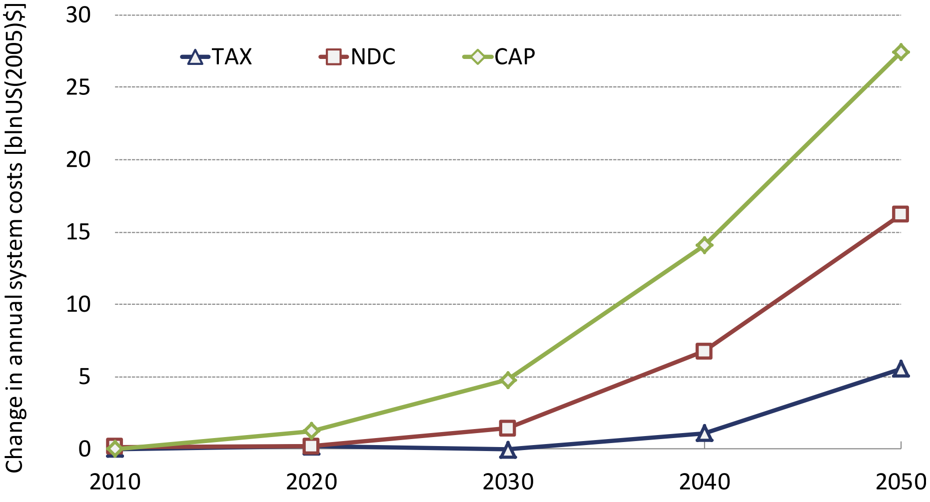

Fig. 9. Relative change in total energy system costs in Kenya with respect to REF until 2050.

emission reductions in 2050, in comparison with the REF scenario.

In 2015 the United Nations introduced the Sustainable Development Goals (SDGs) – a set of 17 objectives to improve the sustainability of human life on Earth by 2030 [27]. The SDGs provide a benchmark to assess a country's current living conditions and future prospects thereof. Focusing on the SDGs that directly address energy and climate change, Kenya appears well positioned to attain a substantial increase of renewable energy share (SDG 7.2). The development of the NDC trajectory is in line with SDG 13.2, targeting the integration of climate change measures into national policies. Compliance thereof would ensure further progress toward the achievement of improvements in energy efficiency (SDG 7.3), and the reduction of adverse environmental impact of cities (SDG 11.6). Universal access to clean and affordable energy (SDG 7.1) remains a challenge that will require attention in the near future, especially for remote villages and rural areas.

The timing of deployment of renewable energy technologies is crucial, as it can greatly affect the maximum obtainable level of GHG abatement in 2030 and 2050. Complacency in this respect, coupled with the rapidly growing energy demand, would imply a longer reliance on imports, and the risk of a lock-in thereof. Early investments are therefore not only essential for achieving Kenya's NDC target, but would also contribute to attaining energy independence and security. Key enablers in this respect are a stable financial climate (see e.g. Refs. [15,33]), and a set of clear, sound and long-term energy policy measures. The latter should facilitate, on the supply side, the deployment of technologies such as based on geothermal, hydro, wind and solar energy, which could provide a large contribution to a nearly carbon-neutral power production mix. On the demand side, we recommend that a transition to modern high-efficiency cooking technologies be prioritised in the residential sector, taking into account not only technical and economic feasibility, but also alignment to specific traditions and priorities of local communities [34]. In the transport sector, a substantial deployment of biofuels should probably be supported, at least in the short term. The principal biofuels we identified in our model runs are Fisher-Tropsch biodiesel for passenger cars and busses, and bioethanol for trucks. In the CAP scenario, a substantial deployment of biofuels is already achieved in 2030, while in the other scenarios it is deferred to 2040 and 2050.

The SNC represents an important first step towards the development of a climate policy framework that builds on a sound analysis of the costs of the most important mitigation options, encompassing not only low-carbon technology deployment, but also infrastructural, legislative and socio-economic improvements. Our results, however, suggest that the figures reported by the GoK may underestimate overall mitigation costs. This entails a risk of establishing inadequate policy instruments to limit climate change. We therefore recommend a validation, and eventual revision and expansion, of the options considered in the SNC and the costs thereof. This is in line with the review process agreed upon at COP-21.

Given the importance of biomass in the Kenyan economy, and the large uncertainties on the impact of land use change and forestry activities, future work should address these topics in more detail. A large consumption of biomass for energy purposes could lead to biodiversity loss, threatening the extinction of unique species in the local flora and fauna. Competition for land between energy and agricultural crops should also be adequately assessed and planned, in order to ensure future availability of affordable food, in a country where over 20% of the population is currently undernourished [35]. A more accurate estimate of the present and future contribution of deforestation and afforestation to GHG emission and abatement, respectively, is also essential in order to identify adequate long-term climate change mitigation measures for Kenya.

The results presented in this paper reveal that significant changes can be expected in the power, energy and transport sectors in Kenya in the coming decades, even in the absence of stringent climate policies. The latter will likely induce deeper modifications in the way energy is produced and consumed. There is a need for a better understanding of how such profound transformations may affect society, and more research efforts should be dedicated to this subject. Specific issues related to the large-scale deployment of new energy technologies (either on the supply or on the demand side) are, amongst others, social acceptance, consequences for the labour market, capacity building and higher education requirements, implications for local tribes and minorities, and potential contributions to poverty relief.

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