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Integrated climate change and air pollution mitigation assessment for Togo

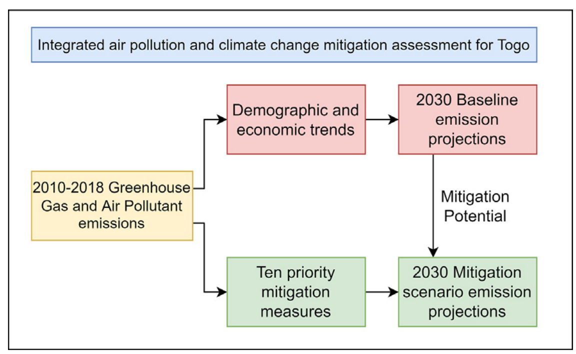
Akpé Agbossou [a], Jérémie Kokou Fontodji [a], Koffi Ayassou [a], Sanonka Tchegueni [a], Kossi Novinyo Segla [a], Kossi Adjonou [a], Yao Bokovi [a], Ayite-Lo Ajayon [a], Aniko Polo-Akpisso [a,b], Johan C.I. Kuylenstierna [c], Christopher S. Malley [c,*], Eleni Michalopoulou [c], Jessica Slater [c]

[a] University of Lomé, Lomé, Togo
[b] National Coordination of NDC Togo, Ministry of Environment and Natural Resources, Lomé, Togo
[c] Stockholm Environment Institute, Department of Environment and Geography, University of York, United Kingdom

HIGHLIGHTS

- Togo in west Africa experiences air pollution levels damaging to human health.
- Mitigation assessment evaluates emission reductions from Togo's climate plans.
- Ten measures could reduce Togo's greenhouse gas emissions by 20 % by 2030.
- Simultaneously, particulate matter air pollutant emissions are more than halved.
- Action on residential biomass cooking key to achieving climate and clean air goals.

GRAPHICAL ABSTRACT



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ABSTRACT

Togo, in west Africa, is vulnerable to the impacts of climate change, but has made a negligible contribution to causing it. Togo ratified the Paris Agreement in 2017, committing to submit Nationally Determined Contributions (NDCs) that outline Togo's climate change mitigation commitment. Togo's capital, Lomé, as well as other areas of Togo have ambient air pollutant levels exceeding World Health Organisation guidelines for human health protection, and 91 % of Togolese households cook using solid biomass, elevating household air pollution exposure. In Togo's updated NDC, submitted in 2021, Togo acknowledges the importance and opportunity of achieving international climate change mitigation targets in ways that improve air quality and achieve health benefits for Togo's citizens. The aim of this work is to evaluate priority mitigation measures in an integrated assessment of air pollutant, Short-Lived Climate Pollutant (SLCP) and Greenhouse Gas (GHG) emissions to identify their effectiveness in simultaneously reducing air pollution and Togo's contribution to climate change. The mitigation assessment quantifies emissions for Togo and Grand Lomé from all major source sectors for historical years between 2010 and 2018, for a baseline projection to 2030 and for mitigation scenarios evaluating ten mitigation measures. The assessment estimates that Togo emitted ~21 million tonnes of GHG emissions in 2018, predominantly from the energy and Agriculture, Forestry and Other Land Use sectors. GHG emissions are projected to increase 42 % to 30 million tonnes in 2030 without implementation of mitigation policies and measures. The implementation of the ten identified priority mitigation measures could reduce GHG emissions by ~20 % in 2030 compared to the baseline, while SLCPs and air pollutants were estimated to be reduced more, with a more than 75 % reduction in black carbon emissions in 2030. This work therefore provides a clear pathway by which Togo can reduce its already small contribution to climate change while simultaneously achieving local benefits for air quality and human health in Togo and Grand Lomé.

* Corresponding author.
E-mail address: chris.malley@york.ac.uk (C.S. Malley).

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1. Introduction

The Togolese Republic (hereafter abbreviated to Togo) in west Africa has a population of 7.5 million people (2019) with a growth rate of 2.3 % (INSEED, 2021; INSEED, 2015). Togo ranks 167 out of 189 countries on the United Nations Development Programme (UNDP) Human Development Index (United Nations Development Programme, 2020). As a result of these development challenges, Togo is vulnerable to the impacts of climate change. Two-thirds of employment in Togo is in the agriculture sector, and climate change-induced changes in weather patterns, e.g. droughts and heatwaves are likely to affect crop production (Togolese Republic, 2021a). Only 9 % of the rural population have access to electricity (World Bank, 2021). Despite this vulnerability, the contribution of Togo to global warming has been negligible (World Bank, 2021).

For many countries, like Togo, that make small contributions to climate change, and which face other development challenges, there have been substantial efforts to identify and evaluate those strategies that can simultaneously achieve climate change mitigation and address national development priorities (Malley et al., 2021b). One of the development benefits that has been most strongly linked to climate change mitigation is reduced air pollutant concentrations (indoors and outdoors), and the resultant reductions in human health impacts associated with exposure to air pollutants such as fine particulate matter ($PM_{2.5}$) and surface ozone (O_3) (Shindell et al., 2012). Approximately 5 million premature deaths per year are associated with exposure to ambient and household air pollution (Murray et al., 2020), as well as millions of cases of non-fatal health outcomes such as asthma exacerbations and adverse pregnancy outcomes (Anenberg et al., 2018; Malley et al., 2017). A large number of global, regional and national assessments have identified the substantial opportunity to simultaneously take actions that reduce GHGs and short-lived climate pollutants (SLCPs), while also reducing air pollutant emissions (Kuylenstierna et al., 2020; Nakarmi et al., 2020; UNEP/WMO, 2011; UNEP, 2019).

Togo has been at the forefront of efforts to integrate air pollution and climate change into national policy making and planning processes. As a member of the Climate and Clean Air Coalition (CCAC) since 2013, Togo has been an active participant in the CCAC's Supporting National Action & Planning on Short-Lived Climate Pollutant (SNAP) initiative. The CCAC is a voluntary coalition of approximately 70 State and 70 Non-State partners that aims to increase actions taken to reduce Short-Lived Climate Pollutants (SLCPs) like methane, black carbon and hydrofluorocarbons (HFCs), and simultaneously mitigate climate change and air pollution. The SNAP initiative provides direct support to State partners to increase capacity for planning on integrate air quality and climate change planning (CCAC SNAP, 2018). Through the SNAP initiative between 2015 and 2019, Togo developed a National Action Plan to Reduce Short-Lived Climate Pollutants and Air Pollutants (Togo Ministry of Environment, 2020).

In 2021, Togo updated in Nationally Determined Contribution (NDC) outlining its climate change mitigation commitment to unconditionally reduce GHG emissions by 20.5 % and up to 50.6 % with international support, with both reductions achieved in 2030 and relative to a baseline scenario (Togolese Republic, 2021a). This reflects an increase in GHG mitigation ambition compared to Togo's Intended NDC, submitted in 2015 (Togolese Republic, 2015). Togo's updated NDC also acknowledges the importance of integrating actions to reduce SLCPs and other air pollutants, stating *'The mitigation of GHGs has been integrated with the mitigation of Short-Lived Climate Pollutants in accordance with the National Plan for the Reduction of Air Pollutants and Short-Lived Climate Pollutants. As a result, the implementation of Togo's revised NDC should result in substantial benefits in terms of reduction of SLCPs and air pollutants, improvement of quality of life, improved air quality and public health.'* (Togolese Republic, 2021a).

The aim of this work is to describe the quantitative assessment of GHG, SLCP and air pollutant mitigation conducted to support integrated air quality and climate change planning in Togo. The assessment evaluates the emission reduction potential of specific mitigation actions across all major source sectors to inform the development of Togo's updated climate change commitment (Togolese Republic, 2021a). This work provides a practical example of how a quantitative assessment of emission reductions can be designed that provides information relevant for the development of integrated plans that simultaneously address global climate change mitigation goals, and local development priorities, such as air pollution. Its application in other countries could help to ensure that climate change plans achieve local benefits, which have previously been argued could i) increase climate change mitigation ambition through the inclusion of additional actions that mitigate climate change because of their local air pollution and health benefits, and ii) could increase implementation of commitments because of the multiple benefits achieved through implementation of the actions that achieve climate change mitigation goals (CCAC SNAP, 2019).

2. Methods

The integrated assessment of air pollutants, short-lived climate pollutants (SLCPs) and greenhouse gases (GHGs) was undertaken using the Low Emissions Analysis Platform (LEAP, Heaps, 2022). Section 2.1 outlines the modelling frameworks used to quantify historic and future emissions in Togo and Grand Lomé for different scenarios for historical years. Section 2.2 describes the sector specific methods and data used.

2.1. Modelling overview

The mitigation assessment was undertaken for three geographic regions. First, emissions were estimated for the whole of Togo. To assess how air pollution could be reduced in Togo's largest city, national emissions were then disaggregated between the capital, Grand Lomé, and the rest of Togo for historic years and future projections of baseline and mitigation scenario emissions. Grand Lomé, includes 30 % of Togo's population, and the majority of economic activity (INSEED, 2021). The mitigation assessment covered GHG, SLCP and air pollutant emissions from all emitting source sectors, categorised within four overarching source sectors, i) Energy, ii) Industrial Processes and Product Use (IPPU), iii) Agriculture, forestry and other land use (AFOLU), and iv) Waste (IPCC, 2006). From these sources, the assessment quantifies emissions of GHGs, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and Hydrofluorocarbons (HFCs). For the non-CO_2 GHGs, the global warming potentials from the IPCC 5th Assessment Report (with climate feedbacks) were used to aggregate all into a single GHG emission metric (Myhre et al., 2013). Emissions of SLCPs, i.e. black carbon (BC) and other air pollutants (organic carbon (OC), fine particular matter ($PM_{2.5}$), nitrogen oxides (NO_x), sulphur dioxide (SO_2), volatile organic compounds (VOCs), ammonia (NH_3) and carbon monoxide (CO)) were also quantified.

The mitigation assessment covered two time periods, i) historic years, and ii) future projections. The historical years covered a core period of 2010–2018 where historical data was available for the majority of sectors. For historical years, emission estimates were calculated by multiplying specific activity data by emission factors. In general, the activity data used for each sector were extracted from relevant national documents, strategies and reports, including Togo's National Inventory Reports and Biennial Update Reports submitted to the United Nations Framework Convention on Climate Change (Togolese Republic, 2021b, 2021c), or provided by national institutions such as the National Institute of Statistics and Economic and Demographic Studies – Togo (INSEED). In some cases, international data sources were used when national data was not available. In all cases, default international emission factors were combined with the activity data, due to a lack of country-specific emission factors developed in Togo (EMEP/EEA, 2019; IPCC, 2019; IPCC, 2006). The methods and data sources used for historical emissions are summarised in Table 1.

Future emission projections were made from 2019 to 2030. For future projections, a 'baseline' scenario first reflected expected socioeconomic development and population growth in Togo, without implementation of specific policies or measures to reduce GHG or air pollutant emissions. The baseline scenario was developed to provide a reference against which the emission reduction potential of different mitigation measures could be evaluated. The key drivers used to project emissions into the future for each sector for the baseline scenario are summarised in Table 2.

The other future scenarios modelled reflected the implementation of different, specific policies and measures designed to reduce GHG emissions. In total 8 specific mitigation measures included in Togo's updated NDC were included in the GHG mitigation assessment as well as 2 additional mitigation measures from Togo's National Action Plan on Air Pollution and SLCPs (summarised in Table 3). These policies and measures were identified from a review of current plans, strategies and policies in Togo. The measures identified were prioritised through stakeholder consultations. At the end of the identification, evaluation and prioritisation process, a final stakeholder consultation workshop was held to validate and endorse the 10 measures those that were considered in the final GHG mitigation assessment. To be modelled, each mitigation measure needed to be described in sufficient detail that it has a target (i.e. level of implementation) and a timeline by which this target would be met, so that its GHG emission reduction potential, compared to the baseline, could be modelled in the mitigation assessment.

Finally, the modelling framework also disaggregated national emissions of GHGs, SLCPs, and air pollutants between Grand Lomé, the municipal area covering Lomé, the capital of Togo, and the surrounding urban area, and the rest of Togo. Table 4 summarises, for each major source sector, the method used to disaggregate emissions between Grand Lomé and the rest of Togo. For the majority of sources national emissions were disaggregated between Grand Lomé and the rest of Togo, e.g. based on the number of households, or number of journeys taken in Grand Lomé vs the rest of the country. However, for the waste sectors, separate emission estimates were made for Grand Lomé and the rest of Togo, based on the availability of data for each region, and then aggregated to give the national total emissions. See Section 2.2 for more details.

2.2. Sector-specific methods for GHG, SLCP and air pollutant emissions

2.2.1. Energy sector

For the energy sector GHG mitigation assessment, an energy system model was developed using LEAP to link energy demand and supply (Togolese Republic, 2021a). The energy demand modules quantified historic and future consumption of solid (e.g. wood, charcoal), liquid (e.g. gasoline, diesel, kerosene, heavy fuel oil, liquified petroleum gas (LPG)) and gaseous (e.g. natural gas) fuels in Togo, as well as consumption of electricity. The consumption of these fuels and electricity were disaggregated into four sub sectors, Residential, Commercial and Public Services, Industry, and Transport. Energy consumption in Agriculture was not included, but is likely to be negligible compared to other sources of energy consumption. The methods for quantifying energy consumption in these subsectors, including the level of disaggregation, specificity of activities consuming each fuel, activity variables etc. are outlined below. In the energy demand modules, where pollutants were emitted directly at the point of consumption (i.e. through combustion of the fuel), the quantity of fuel consumed were modelled and multiplied by sector, fuel, and technology-specific international default emission factors (EMEP/EEA, 2019; IPCC, 2006).

Those GHG emissions that are not directly emitted at the point of final energy consumption are accounted for under the energy supply module. In the case of Togo, with no domestic oil or gas resources, the energy supply subsectors were electricity generation, and charcoal production. The GHG mitigation assessment included only GHG emissions that are emitted within

Table 1
Summary of data sources used to estimate GHG emissions for each source sector.

Source sector	Activity data	Source of data
1A1a Public electricity and heat production	Historical electricity generation Fuel consumption Power plant capacity, Efficiency and availability	National Energy Balance (MME/DGE, 2018)
1A2 Manufacturing industries and construction	Fuel and electricity consumption in industrial sector for the following sub-sectors: - Non-metallic minerals - Food, beverage and tobacco - Construction - Other industries	National Energy Balance (MME/DGE, 2018)
1A3b Road transportation	Number of vehicles Average distance travelled per vehicle per year Load factor for passenger and freight vehicles	Road and Rail transport Directorate of Togo, Ministry of Environment of Togo (Freitas, 2020) National Institute of Statistics and of Economic and Demographic Studies (INSEED, 2021) Global Transportation Roadmap Model (ICCT, 2012)
1A4a Commercial/institutional	Fuel consumption in services sector	National Energy Balance (MME/DGE, 2018)
1A4b Residential	Fuel consumption in household sector Number of households Number of households cooking using different fuels and technologies	National Energy Balance (MME/DGE, 2018) National Institute of Statistics and of Economic and Demographic Studies (INSEED, 2021)
2A Mineral industry	Cement production	National Greenhouse Gas Emission Inventory (Togolese Republic, 2021b)
2F Product uses as substitutes for ozone depleting substances	Refrigeration and air conditioning	National Greenhouse Gas Emission Inventory (Togolese Republic, 2021b)
3A Livestock	Number of animals	FAOStat (FAO, 2022)
3B Land	Land (forest, plantation, crop, grassland, wooded grassland, wetland, settlement) remaining land type Land converted to other land types Land use parameters (e.g. biomass growth rates)	National Greenhouse Gas Emission Inventory (Togolese Republic, 2021b)
3C Aggregate sources and non-CO2 emission sources on land	Rice production	FAOStat (FAO, 2022)
3D Other		
4A Solid waste disposal on land	Per capita waste generation rates Waste collection rates Urban population	National Greenhouse Gas Emission Inventory (Togolese Republic, 2021b)
4D Liquid waste	Wastewater treatment systems	National Greenhouse Gas Emission Inventory (Togolese Republic, 2021b)

Table 2
Assumptions about socioeconomic development in Togo that informed the development of the baseline scenario.

Source sector	Variable used for baseline projections	Value	Source of data
1A1a Public electricity and heat production	New installed capacity for electricity generation	Centrale thermique CEET: 50 MW in 2025 Centrale Kekeli: 65 MW in 2021	Revised NDC (Togolese Republic, 2021a)
1A2 Manufacturing industries and construction	Fuel consumption in industrial sector	Growth in energy consumption in industrial subsectors: Non-metallic minerals: 2 % per year Food, Beverage and Tobacco: 1 % per year Construction: 1 % per year Other industries: 1 % per year	Revised NDC (Togolese Republic, 2021a)
1A3b Road transportation	Passenger-km (passenger transport demand)	12 % per year increase	Revised NDC (Togolese Republic, 2021a)
	Tonnes-km (freight transport demand)	6 % per year increase	
1A4a Commercial/institutional	Fuel consumption in services sector	All fuels: 1 % per year Electricity: 2 % per year	Revised NDC (Togolese Republic, 2021a)
1A4b Residential	Number of households	Population growth: Population 2010: 6.191 million 2015: 6.835 million 2018: 7.352 million 2020: 7.706 million 2025: 8.624 million 2030: 9.575 million	Revised NDC (Togolese Republic, 2021a)
	% Households urban	42 % urban in 2018; 50.5 % urban in 2030	
	Electricity access	Urban: 84 % access in 2018, 100 % in 2030 Rural: 9 % access in 2018, 100 % in 2030	
2A Mineral industry	Cement production	1 % growth per year	Revised NDC (Togolese Republic, 2021a)
2F Product uses as substitutes of ozone depleting substances	Refrigeration and air conditioning	Consumption: 2013–2020 average consumption	Revised NDC (Togolese Republic, 2021a)
3A Livestock	Number of animals	2.3 % per year growth	Revised NDC (Togolese Republic, 2021a)
3B Land	Land (forest, plantation, crop, grassland, wooded grassland, wetland, settlement) remaining land type	Deforestation/afforestation rates, annual biomass growth rates, losses due to disturbances remain at 2015–2018 average values.	Revised NDC (Togolese Republic, 2021a)
	Land converted to other land types	Biomass losses due to fuelwood grow at rate of biomass consumption in residential and commercial energy sectors.	
3C Aggregate sources and non-CO2 emission sources on land	Rice and other crop production Amount of fertilisers applied Area burnt in grasslands, forestland, croplands	2.84 % per year growth in rice production 2.3 % per year increase in fertiliser consumption	Revised NDC (Togolese Republic, 2021a)
3D Other			
4A Solid waste disposal on land	Municipal solid waste generated	Population growth rate	Revised NDC (Togolese Republic, 2021a)
4D Liquid waste	Wastewater generated	Population growth rate	Revised NDC (Togolese Republic, 2021a)

the territorial boundaries of Togo. For biomass, the consumption of biomass results in CO_2 emissions at the point of combustion. However, emissions of CO_2 from biomass consumption are not accounted for under the energy sector emissions calculations within LEAP. The net CO_2 emissions from consumption of biomass in the energy sector is included within the agriculture, forestry and other land use (AFOLU) sector calculations, in which the change in biomass stocks in forests and other land use types from the use of biomass for energy is accounted for, alongside other processes that change the size of carbon sources and sinks from land, as described in Section 2.2.3.

In the Residential sector, total consumption of fuels and electricity was calculated by multiplying the average household fuel consumption for cooking, lighting and other electricity consumption, estimated for urban and rural households separately, by the total number of urban and rural households using different types of fuels and technologies for those activities, respectively. Within urban and rural households, energy consuming activities were disaggregated between i) cooking, for which wood, charcoal (using existing efficiency and more efficient technology stoves), LPG, biogas and wood briquettes (the latter two only used in the mitigation scenarios) were cooking fuel options, ii) lighting, where electricity and kerosene were the two fuels options, and iii) other energy use, which included electricity consumption for activities other than cooking and lighting. The total number of urban and rural households were calculated based on the urban and rural population, and average household size, using statistics provided

Table 3
Summary of mitigation measures evaluated for GHG emission reduction potential from plans and strategies in Togo.

Sector	Mitigation measure	Plan/strategy
Electricity Generation	Expansion of renewable electricity generation: - 50 MW solar in 2021, 99 MW in 2023 - 86.2 MW additional hydro capacity in 2023	Revised NDC (Togolese Republic, 2021a) National Renewable Energy Action Plan (PANER) (Ministry of Mines and Energy of Togo, 2015)
Transport	Increase percent of electric vehicles in fleet: - 1 % of passenger cars electric by 2030	Revised NDC (Togolese Republic, 2021a) National Renewable Energy Action Plan (PANER) (Ministry of Mines and Energy of Togo, 2015)
Transport	Improve efficiency of transport: 20 % improvement in fuel efficiency of vehicle fleet in Togo by 2030	Revised NDC (Togolese Republic, 2021a)
Residential	Increase percentage of households cooking using clean fuels or more efficient biomass stoves By 2030: Urban Households: - 35 % of urban households cooking using LPG - 12 % of urban households cooking using biogas - 15 % of urban households cooking using biomass briquettes - 72 % of urban households cooking using wood switch to more efficient biomass stoves (20 % more efficient than base case energy consumption shown in Table 5) - 90 % of urban households cooking using charcoal switch to more efficient biomass stoves (48 % more efficient than base case energy consumption shown in Table 5) Rural Households: - 8 % of rural households cooking using LPG - 15 % of rural households cooking using biogas - 10 % of rural households cooking using biomass briquettes - 72 % of rural households cooking using wood switch to more efficient biomass stoves (20 % more efficient than base case energy consumption shown in Table 5) - 90 % of rural households cooking using charcoal switch to more efficient biomass stoves (48 % more efficient than base case energy consumption shown in Table 5)	Revised NDC (Togolese Republic, 2021a)
Charcoal Production	Increase charcoal produced using more efficient kilns (26 % efficiency vs 11 % efficiency in baseline) – 100 % conversion by 2030	Revised NDC (Togolese Republic, 2021a)
Agriculture	Reduction in emission intensity of livestock and crop production: 1 % per year reduction in methane emissions from enteric fermentation and manure management 1 % per year reduction in fertiliser consumption 1 % per year reduction in land continuously flooded for rice production 2 % per year reduction in crop residue openly burned in fields	Revised NDC (Togolese Republic, 2021a)
Forestry	Implementation of residential cooking measures above reducing fuel wood demand 5 % reduction in forest area under forest fire by 2030 compared to 2018 levels 5 % increase in land converted to forest land in 2030 compared to 2018 levels (i.e. 86,000 ha y^{-1} converted to forest land by 2030)	Revised NDC (Togolese Republic, 2021a)
Waste	4500 t methane recovered from landfill sites through landfill gas capture by 2030	Revised NDC (Togolese Republic, 2021a)
Transport	100 % of vehicles meet Euro IV vehicle emission standards by 2040	National Action Plan on Air Pollutants and SLCPs (Togo Ministry of Environment, 2020)
Waste	Reduce open burning of waste by 30 % by 2030	National Action Plan on Air Pollutants and SLCPs (Togo Ministry of Environment, 2020)

by the National Institute of Statistics and Economic Development Studies (INSEED, 2021) (Table S1). The percentage of households in urban and rural areas cooking using different types of fuels, and with access to electricity were obtained from official statistics provided by the General Directorate of Energy, Ministry of Mines and Energy of Togo (DGE/MME, summarised in Table S1). Energy intensities (the energy consumption per household per year for cooking and other electricity consumption) were also provided by DGE/MME. The value of these variables in 2018 is shown in Table S1. For the baseline scenario, the number of households in urban and rural areas was projected to increase in the future according

Table 4
Assumptions used to disaggregate emissions between Lomé and the rest of Togo.

Source sector	Assumption	Reference
1A1a Public electricity and heat production	All power stations are outside Grand Lomé	Expert knowledge
1A2 Manufacturing industries and construction	88.9 % of national industries are within Grand Lomé	(INSEED, 2021)
1A3b Road transportation	70 % of passenger and freight transport occurs in Grand Lomé	(INSEED, 2021)
1A4a Commercial/institutional	63.5 % of commercial and public services are based on Grand Lomé	(INSEED, 2021)
1A4b Residential	Number of households in Grand Lomé calculated based on 30 % of national population in Grand Lomé, and household size 4.5 people per households in Grand Lomé	(INSEED, 2021)
3A Livestock	All agriculture occurs outside Grand Lomé	Expert knowledge
3B Land	All Forestry occurs outside Grand Lomé	Expert knowledge
3C Aggregate sources and non-CO_2 emission sources on land	All agriculture occurs outside Grand Lomé	Expert knowledge
3D Other	All agriculture occurs outside Grand Lomé	Expert knowledge
4A Solid waste disposal on land	N.A. - Separate bottom-up estimates of emissions from solid waste made for Grand Lomé and other urban areas based on specific population and waste generation rates for each region	(Togolese Republic, 2021b)
4D Liquid waste	Disaggregated based on 30 % population within Grand Lomé	(INSEED, 2021)

to projected population growth rate (Table 2). The percentage of households cooking using different fuels was projected to remain the same as in 2018 (i.e. the values shown in Table S1). However, the baseline projected a large increase in the percentage of households with access to electricity, with 100 % of households projected to have access to electricity by 2030, in line with Togo's Electrification Strategy (MME, 2018). This resulted in a reduction in the number of households using kerosene for lighting in the baseline scenario compared to 2018. The mitigation scenarios reflected the implementation of two measures in the residential sector, i) the increased penetration of clean fuels (electricity and LPG) for cooking, and the increased use of more efficient biomass stoves for cooking (Table 3).

In Industry, and Commercial and Public Services, there was insufficient data to disaggregate energy consumption into sub-activities. Therefore, for historical years, the total consumption of different types of fuel in each sector was taken directly from Togo's National Energy Balances for 2010–2018 (MME/DGE, 2018), and multiplied by fuel and sector-specific international default emission factors to quantify historical GHG, SLCP and air pollutant emissions from each sector. For the industry sector, fuel consumption in four industrial sub-sectors were available separately. The type and quantity of fuels consumed in each sector in 2018 is shown in Table S2. For the baseline scenario, fuel consumption in each sector was projected to increase at between 1 and 2 % per year, as outlined in Togolese Republic (2021a) (Table 2).

In the transport sector, total fuel consumption was estimated for road transport only, due to a lack of data on the fuel consumption for other transport modes, and because road transport represents the dominant transport mode in Togo. Road transport emissions were estimated separately for passenger and freight transport, using the number of passenger-km, and tonnes-km, respectively, as the activity variables to estimate transport demand. The number of passenger-km and tonnes-km taken by road vehicles was calculated based on country-specific data on the number of vehicles of different types (Table 1). Data on the number of vehicles in the vehicle fleet for motorcycles, passenger cars, taxis, minibuses and buses were multiplied by default, international annual average distance travelled, and occupancy rates to estimate the number of passenger-km travelled by each of these vehicle types (ICCT, 2012). The number of passenger-km taken by each vehicle type was the broken down by fuel (percentage of vehicles using gasoline and diesel, taken from Freitas (2020)) and vehicle emission standards (Euro standard, based on average vehicle age) as shown in Table S3. The same approach was used for freight road transport, in which the number of tonnes-km were the activity variable, and were estimated for light commercial vehicles, medium duty vehicles and heavy duty vehicles separately based on the number of vehicles in the fleet (Freitas, 2020), load factors and average distance travelled (ICCT, 2012) (Table S3). The number of passenger-km and tonnes-km for each road transport vehicle type, fuel and Euro standard, were then multiplied by default energy intensities (quantity of fuel per passenger/t-km travelled), and emission factors for each pollutant (EMEP/EEA (2019)). For the baseline scenario, the passenger and freight demand were projected to increase by 12 % and 6 % per year, respectively, reflecting both population and GDP increases in Togo (Togolese Republic, 2021a). The share of road transport vehicle types, fuels and Euro standards were kept constant in the baseline scenario.

In the transformation sector, the requirements for electricity generation were based on the domestic demand for electricity (modelled as described above for the energy demand sectors), and imports and exports for the losses from electricity transmission and distribution. Transmission and distribution losses were estimated to be 16.44 % in historic years, based on Togo's national energy balance (MME/DGE, 2018), which increased to 18 % in 2020 before remaining constant for the rest of the baseline scenario (Togolese Republic, 2021b, 2021c). One mitigation measure modelled the effect of reducing in transmission and distribution losses on electricity generation and associated emissions (Table 3).

The electricity generation system was modelled for five types of power stations, summarised in Table S48. The key characteristics, of the power plants, such as installed capacity, efficiency, and availability are shown in Table S4. Emissions from power generation were calculated by multiplying the total fuel consumption by fuel and sector-specific international default emission factors for each pollutant. The installed capacity, and availability were used to estimate the amount of electricity generated from each power plant, and combined with the efficiency to estimate future fuel consumption for generating electricity. The baseline scenario reflects the additional electricity generating capacity from fossil fuel sources, specifically expansion of diesel electricity generation through the central thermal power plants (Table S4). The mitigation scenarios reflected additional renewable electricity generation capacity (hydro, solar) (Table 2).

2.2.2. Industrial processes and other product use (IPPU) sector

The emissions from the IPPU sector reflect the process emissions from industry, i.e. the non-fuel combustion emissions associated with particular industrial processes. Only cement production was included in the assessment, due to a lack of data on other industrial process emission sources. The IPCC (2006) Tier 1 methodology was used and estimates CO_2 emissions by multiplying the production or consumption of a particular industrial product by sector-specific emission factors. The key data sources for the IPPU sector data were Togo's 2nd Biennial Update Report and National GHG Inventory Report (Togolese Republic, 2021b, 2021c) (Table S5). In the baseline scenario, the production of the different industrial products included in Table S5 were projected to increase by 1 % per year (Table 2), as detailed in Togolese Republic (2021a).

The IPPU sector also includes the consumption of ozone depleting substances (ODS). In this analysis the emissions from the consumption of hydrofluorocarbons (HFCs) were quantified historically and projected into the future using the IPCC Tier 1 methodology (IPCC, 2006). The only data available in Togo on the consumption of HFCs is the annual total import of HFCs into Togo (there is no domestic production of HFCs). Refrigeration and air conditioning are typically the dominant use of HFCs, and it was therefore assumed that all HFCs imported into Togo were used for this application. The IPCC Tier 1 methodology for contained HFC applications was used and estimated the annual emissions of HFCs by i) applying an emission factor to the bank of HFCs (% of bank lost per year), and ii) estimating the total HFC contained in equipment that is retired in the target year, and assuming it is emitted if not specifically destroyed to prevent emission. Data on HFC imports was available between 2013 and 2018. Using this data, and IPCC (2006) Tier 1 assumptions for annual loss from HFC bank (15 % per year), equipment lifetime (15 years), and assuming all HFC is emitted at the end of the equipment's life, the bank and annual HFC emissions were calculated for 2013–2018, and for the baseline scenario in which HFC imports were estimated to continue at the 2013–2018 average import rate (Table 2). For HFCs, the mitigation measure included in the assessment reflects the implementation of the HFC phasedown schedule in the Kigali Amendment to the Montreal Protocol for Annex 5 countries (i.e. freezing HFC consumption in 2024, and a 10 % reduction in HFC consumption in 2029 compared to 2021 levels) (Table 3).

2.2.3. Agriculture, forestry and other land use

The AFOLU sector includes emissions from agricultural activities taking place on farms (emissions from food and beverage processes are included above in IPPU emissions), as well as the emissions and removals of CO_2 from the atmosphere from forestry and other land use. For agriculture, emissions were estimated for subsectors including livestock enteric fermentation (CH_4), manure management (CH_4, N_2O), application of manure and synthetic fertiliser to managed soils (N_2O), rice cultivation (CH_4), and agricultural residue burning (CH_4, N_2O, as well as SLCPs and air pollutants). For each of these sectors, IPCC (2006) Tier 1 methods were used to estimate emissions. The key activity data used with these methods was taken from FAOStat (2022).

For CH_4 and N_2O emissions from enteric fermentation and manure management, the number of animals in each ruminant animal category (Table S6) was multiplied by regional specific emission factors from IPCC (2019). For agricultural residue burning, the total mass of crop residue burned in fields was estimated by multiplying the annual crop production

(Table S6) by a crop to residue ratio (default values from EMEP/EEA (2019)), and fraction of crop residue burned in fields. Methane emissions from rice production were calculated by multiplying the annual area harvested, disaggregated between flooded and rainfed water management regimes (Table S6), by an average cultivation period (default IPCC (2019) value for Africa), baseline methane emission factor, and scaling factor for water management regime, based on the IPCC (2006) Tier 1 methodology. Finally, the emissions of N_2O emitted from nitrogen applied to managed soils (crop and pasture land) were estimated based on the annual nitrogen applied to soils as manure and synthetic fertiliser (Table S6), and default direct and indirect (volatilisation) N_2O emission factors (IPCC, 2019).

For the forestry and other land use component of the AFOLU sector emissions (and removals), the IPCC Tier 1 methods were used to quantify the net emissions of CO_2 from different land use types. Within this FOLU analysis, sufficient data was available to characterise emissions for three processes within the FOLU sector, i) net GHG emissions from Forest land remaining Forest land, ii) net GHG emissions from C sequestration for other land converted to Forest land, and iii) net GHG emissions from deforestation, i.e. Forest land converted to other land. The key data and assumptions used to estimate the net GHG emissions from these sources is summarised in Table S7. Estimates of net GHG emissions from the FOLU sector were estimated for 1995–2018 for historic years, and then projected to 2030 for the baseline assuming a continuation of historic trends in terms of land conversion rates, i.e. those included in Table S7.

For Forest land remaining forest land, the net CO_2 emissions were calculated based on the difference between biomass gains, i.e. annual biomass growth in forests, and losses, for which wood removals, fuelwood, and disturbances (fires) were taken into account using IPCC Tier 1 approaches. Carbon pools in dead organic matter and litter were not accounted for in this analysis. For land converted to forest land, the default IPCC (2006) assumption that land remains in this category for 20 years before conversion is complete was made. The average annual biomass growth rates shown in Table S7 for different other land converted to forest land were used to estimate the CO_2 sequestered from increased biomass growth. Changes in soil carbon, dead organic matter and litter carbon pools were not included due to lack of data. Finally, for forest land converted to other land, the default biomass stocks in Forest from IPCC (2006) were used to estimate the net emissions from this conversion from the loss of these biomass stocks.

2.2.4. Waste sector

The GHG emissions from the waste sector were quantified for municipal solid waste (CH_4 emissions from landfill, and GHG, SLCP and air pollutant emissions from open burning of waste) and domestic wastewater (CH_4 emissions only) using IPCC (2006) Tier 1 methodologies. For municipal solid waste (MSW), emissions were estimated by first estimating the total MSW generated, and apportioning between different waste streams. The total MSW generated was calculated for the urban population only, due to a lack of data on rural waste generation rates, composition and collection rates. The urban populations for Grand Lomé and the rest of Togo were multiplied by per capita waste generation rates, and the composition fraction for different waste types, which were obtained from Togolese Republic (2021b) (see Table S8 for 2018 values). The quantity of waste generated of each type was then separated between the waste that was formally collected, and the waste that was uncollected. For the waste formally collected, all was assumed to be treated at landfill sites, either managed anaerobic, or unmanaged shallow landfills (Table S8). The generation of methane from the organic waste that ends up at these landfill sites was then calculated using IPCC (2019) Tier 1 default parameters for degradable organic content (DOC) of different waste types, and methane correction factors for different landfill types.

For domestic wastewater, emissions from the wastewater of the urban population was considered, due to a lack of data on wastewater treatment types in rural areas. The IPCC (2019) regional default biological oxygen demand (BOD) (13.5 kg/person/year) value was multiplied by the urban population of Togo to estimate the total mass of organic content in urban domestic wastewater in each year. This organic component of urban domestic wastewater was then disaggregated between different wastewater treatment types (Table S8), and multiplied by the IPCC (2019) default methane producing capacity (0.6 kg CH_4/kg BOD), and treatment type-specific default IPCC correction factors to estimate the total methane emissions produced from urban domestic wastewater.

In the baseline scenario, the total amount of urban MSW and domestic wastewater generated were projected to increase with the urban population in Grand Lomé and the rest of Togo. The mitigation scenarios reflected implementation of methane capture at landfill sites (Table 3).

2.3. Uncertainty assessment

Within the mitigation assessment, there are several sources of uncertainty. This includes uncertainty in input data such as the activity data used to characterise each major emission source, as well as the uncertainty in the emission factors. There is also uncertainty in the assumptions used to project emissions, and in the ambition and timeline for implementation of the mitigation measures included in the mitigation scenarios. The activity data used in this study reflects official statistics collected in Togo by national institutions (Table 1). The baseline and mitigation scenario assumptions also reflect Togo's national development vision outlined in Government documents, i.e. Togo's updated NDC. This aim of this paper is not to evaluate the robustness of national statistics or projected development. This paper aims, for a given representation of Togo's demographics, economy, energy consumption and supply, agriculture and waste sector characteristics (in the past, present and future), to estimate the GHG, SLCP and air pollutant emissions in Togo associated with this representation.

Therefore, uncertainties in the representation of Togo's key emitting sectors (i.e. the activity data used for historical years and the assumptions used for future projections) are discussed qualitatively in Section 4.2. The uncertainty in the estimated GHG, SLCP and air pollutant emission estimates for each representation is quantified based on the uncertainty in the emission factors used in each sector. As outlined above, international default emission factors were used in this work due to the absence of measured emission factors in Togo. For each pollutant, and source sector, the 95 % confidence intervals (represented as the percentage difference from the central estimate) for each emission factor were taken from the emission factor references, i.e. predominantly IPCC (2006) for Greenhouse Gases, and EMEP/EEA (2019) for black carbon and other air pollutants. The combined uncertainty in national total GHG, SLCP and air pollutant emissions in each scenario was estimated by calculating the square root of the sum of squares of the individual 95 % confidence intervals for each emission factor. This provided the combined percent change from the central estimate for the 2.5th and 97.5th percentile, which were the used to estimate the absolute 95 % uncertainty range in national total emissions. The uncertainty in the results are discussed in Section 4.2.

3. Results

The climate change and air pollution mitigation assessment for Togo first describes historic GHG, SLCP and air pollutant emissions, their disaggregation between Grand Lomé and the rest of Togo, and future projections for the baseline scenario without implementation of any policies or measures designed to reduce emissions (Section 3.1). Section 3.2 describes the impact of implementing the policies and measures summarised in Table 3 on the magnitude of GHG, SLCP and air pollutant emissions in Togo.

3.1. Historical GHG emissions and baseline projections to 2030

Between 2010 and 2018, total GHG emissions in Togo ranged between 16 million tonnes CO_2-equivalent emissions in 2010 and 21 million tonnes in 2018. On average, Forestry and Other Land Use was the largest net GHG emitting sector, with a 2010–2018 average net emission of 10 million tonnes CO_2-equivalent (55 % of the 2010–2018 average total GHG emissions). The energy sector was the second largest source, emitting

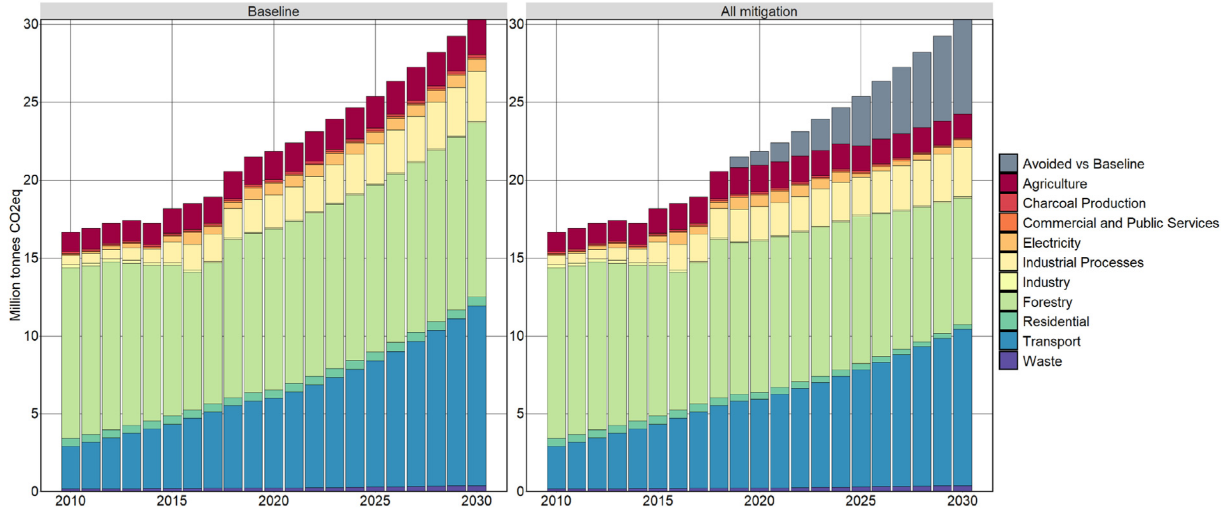

Fig. 1. National total GHG emissions (including all sources and sinks from FOLU) in Togo between 2010 and 2018 (historical years) and 2019–2030 for a) the baseline scenario, and b) implementation of all measures included in the mitigation assessment.

approximately 5 million tonnes CO_2-equivalent GHG emissions on average between 2010 and 2018 (29 % of the average 2010–2018 total GHG emissions). Transport contributed the majority of GHG emissions from the energy sector, with industry, electricity generation and residential contributing the majority of the remaining fraction (Fig. 1). Of the remaining sources, agriculture contributed 8 % of total GHG emissions, while IPPU and waste 6 % and 1 %, respectively (Fig. 1).

The contribution of major emission sources differ for different gases and particles (Table 5, Fig. 2). For carbon dioxide, 60 % of the net-CO_2 emissions come from the Forestry and Other Land Use sector in 2018, with 30 % from transport. The majority of methane emissions were emitted from the agriculture sector, with the residential energy (biomass) combustion, and waste sectors also making substantial contributions. For Short-Lived Climate Pollutants (black carbon), and air pollutants, the residential sector is the largest source, contributing 80 % of black carbon emissions, and a majority of other particulate matter air pollutant emissions (organic carbon, and overall $PM_{2.5}$), reflecting the large fraction of the population relying on biomass for cooking and substantial particulate matter emissions from these sources. Charcoal production, largely for consumption in households for cooking, was also a major source of particulate matter air pollution emissions (Fig. 2). For gaseous nitrogen oxide (NO_x) emissions, the transport sector was the largest source in 2018, but there were also substantial contributions from the residential sector and charcoal production (Fig. 2).

The majority of national total emissions of GHGs, SLCPs and air pollutants occur outside of Grand Lomé. For GHGs, this reflects that the largest source of net-GHG emissions is from the forestry sector, which is predominantly located outside of Grand Lomé (Fig. 3). It also reflects that there is little agriculture in Grand Lomé, and therefore for non-CO_2 GHGs like methane, the largest source was from the agriculture sector in the rest of Togo (Fig. 3). Within Grand Lomé, the largest source of GHGs was from transport and industry sectors. For air pollutant emissions, the two largest sources of particulate matter air pollutant emissions nationally are residential cooking and charcoal production. Almost all production of charcoal occurs outside of Grand Lomé, even though a large fraction of the population in Grand Lomé cook using charcoal. The majority of wood and other

Table 5
National total emissions of GHGs, SLCPs and air pollutants for 2010, 2015 and 2018 (historical years) and for 2020, 2025 and 2030 for a baseline scenario (unit: thousand metric tonnes). The 95 % Confidence Intervals represent the percentage uncertainty in emission estimates associated with the emission factors used in the assessment.

	2010	2015	2018	2020	2025	2030	95 % Confidence Intervals (%)
Carbon dioxide	14,729	15,326	17,127	18,261	21,603	26,054	(−24 %: +24 %)
Carbon monoxide	341	409	470	498	624	801	(−23 %: +60 %)
Methane	58.0	70.5	77.7	81.6	92.6	105.1	(−17 %: +20 %)
Non methane volatile organic compounds	33.9	41.0	47.5	50.3	63.9	83.5	(−32 %: +124 %)
Nitrogen oxides	17.7	22.7	26.1	28.9	36.2	46.1	(−14 %: +31 %)
Nitrous oxide	0.79	1.00	1.09	1.15	1.35	1.60	(−15 %: +30 %)
Sulphur dioxide	4.01	7.65	6.82	11.42	11.47	11.87	(−32 %: +32 %)
Ammonia	3.40	3.84	4.20	4.41	5.03	5.75	(−23 %: +74 %)
PM_{10}	34.1	39.9	41.8	46.7	50.4	54.1	(−21 %: +41 %)
$PM_{2.5}$	30.5	35.3	37.0	41.1	44.4	47.7	(−21 %: +41 %)
Black carbon	8.79	9.10	8.61	9.38	9.56	9.48	(−26 %: +28 %)
Organic carbon	10.9	12.2	13.2	13.8	15.4	17.1	(−27 %: +53 %)

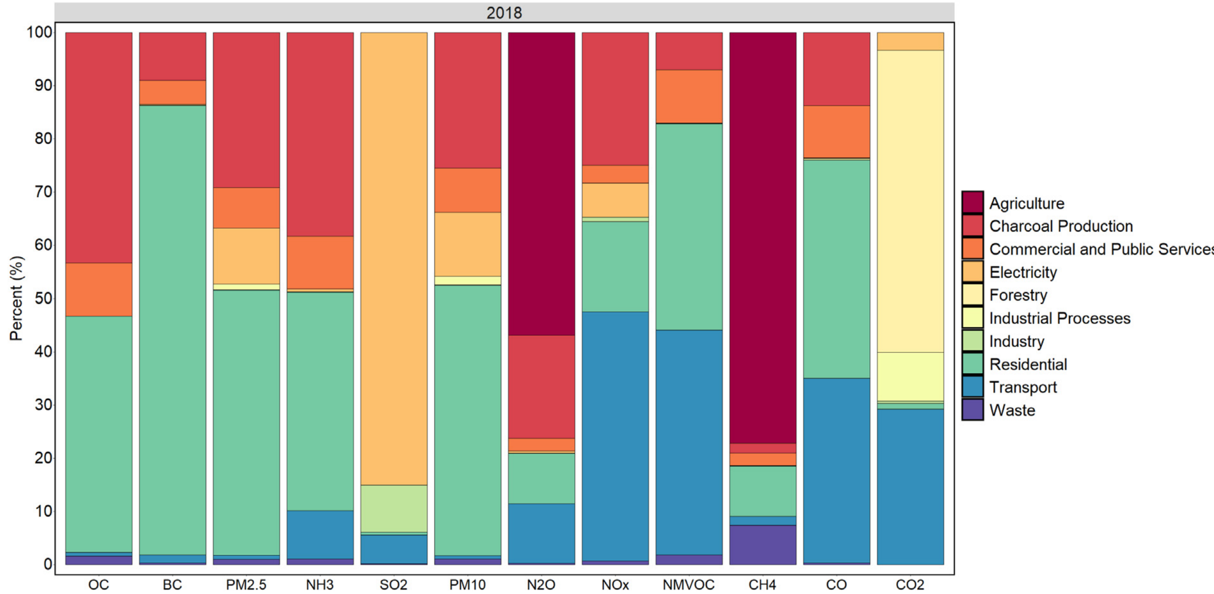

Fig. 2. Contribution of different major emitting source sectors to total emissions of GHGs, SLCPs and air pollutants in Togo in 2018.

biomass consumption used for cooking is consumed in households outside of Grand Lomé. Therefore, for $PM_{2.5}$ emissions, almost 80 % of the national total emissions come from residential consumption, and charcoal production, which predominantly occur outside of Lomé. Therefore, only approximately 12 % of national total $PM_{2.5}$ emissions are estimated to occur within Grand Lomé (Fig. 3). Within Grand Lomé, the residential

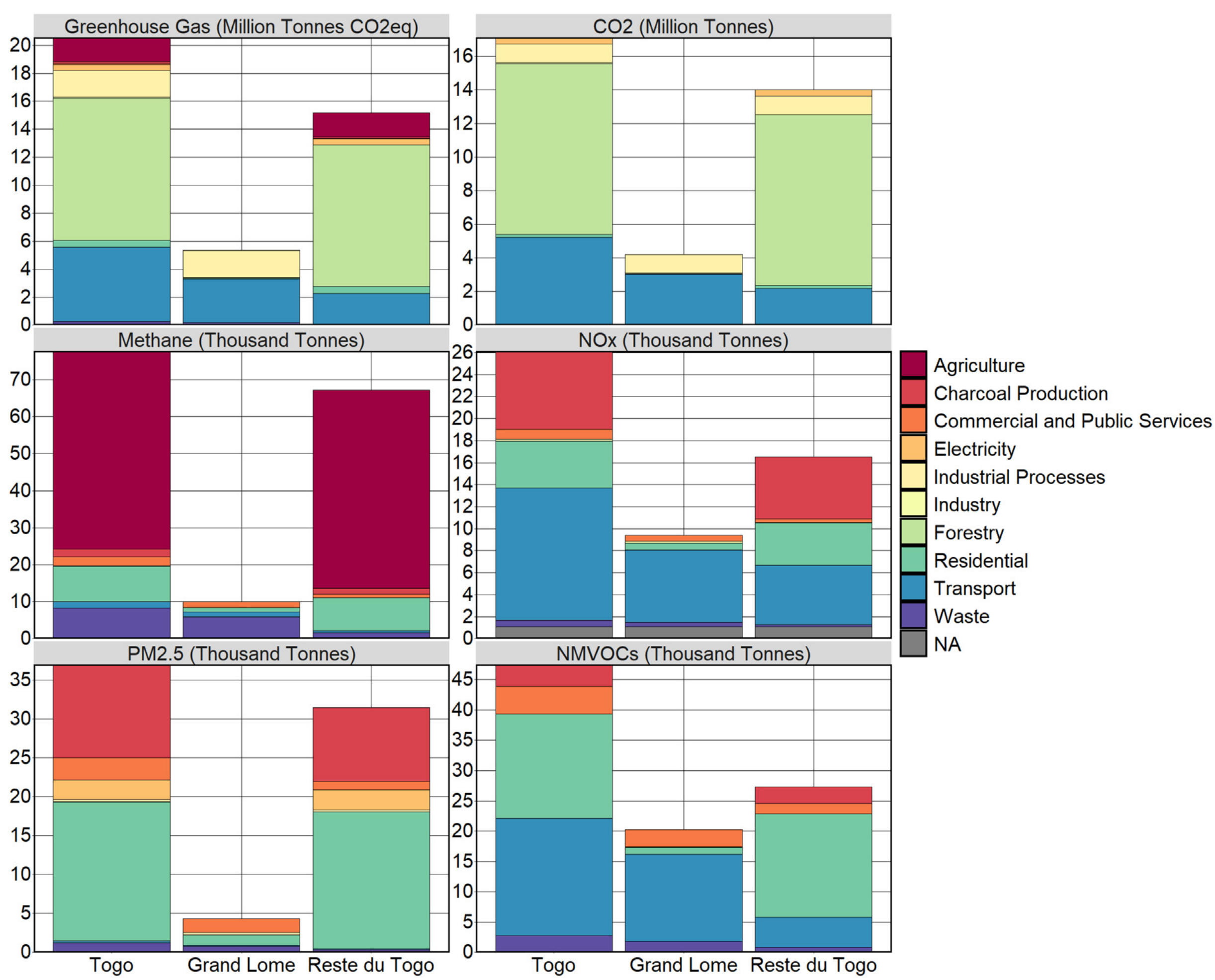

Fig. 3. Emissions of GHGs, SLCPs and air pollutants in 2018 disaggregated between Grand Lomé and the rest of Togo.

sector, biomass consumption in commercial and public services, and open burning of waste, are the three main sources of $PM_{2.5}$ emissions, while the transport sector also makes a small contribution (Fig. 3). Larger fractions of gaseous air pollutant emissions were estimated to occur within Grand Lomé, particularly those associated with transport emissions, which are disproportionately located within Grand Lomé. For nitrogen oxides and non-methane volatile organic compound emissions, 36 % and 43 % of national total emissions occurred within Grand Lomé, with the transport sector the largest source. Outside of Grand Lomé, charcoal production and residential cooking were the largest source of these pollutants.

Total GHG emissions in the baseline scenario are approximately 30 million tonnes CO_2-equivalent in 2030, a 43 % increase compared to 2018 levels (Fig. 1). The energy sector, predominantly transport, becomes the largest source of GHG emissions in 2030, accounting for 44 % of national total GHG emissions in 2030. Forestry and Other Land Use contributes 37 % of total GHG emissions in 2030, and increases at a lower rate compared to the energy emission sources. Emissions of black carbon and other air pollutants such as $PM_{2.5}$ are projected to also increase but at a lower rate, 10 % and 21 % for BC and $PM_{2.5}$, respectively, due to differences in the contribution of major sources to these pollutants compared to GHG emissions (Fig. 2). The baseline scenario therefore emphasises that without the implementation of policies and measures that target emission reductions in major GHG-emitting source sectors, Togo's relatively small contribution to climate change is likely to increase. However, the inclusion of co-emitted SLCPs and air pollutants also highlights that the baseline scenario is likely to result in increases in local impacts in Togo, through increased exposure to health-damaging air pollutants, particularly for those population groups that live in households cooking using wood and other biomass fuels.

3.2. Mitigation potential of GHG mitigation measures

In total, ten mitigation measures were evaluated for their individual, and collective potential to decrease Togo's GHG emissions, and simultaneously reduce emissions of SLCPs, and air pollutants. This included eight mitigation measures included in Togo's updated NDC and two additional measures from Togo's National Action Plan to Reduce Air Pollution and SLCPs. The full implementation of the ten mitigation measures included in this assessment could collectively reduce GHG emissions by approximately 20 % in 2030 compared to the baseline scenario emissions. The largest absolute reductions in GHG emissions occur in the AFOLU sector, followed by the energy sector (Fig. 1, Table 6).

The reduction in GHG emissions from the implementation of the ten mitigation measures individually is shown in Table S9 and Fig. 4, for the whole of Togo, and for Grand Lomé and the rest of Togo individually. The measures to reduce net GHG emissions from the FOLU sector are the most effective at reducing overall GHG emissions from Togo. Of the NDC measures covering the energy sector, increasing the efficiency of the vehicle fleet, and increasing the electricity generated from renewable sources has the potential to achieve the largest reduction in energy sector GHG emissions (Table S9). After implementation of all mitigation measures included in the mitigation assessment, the transport and Forestry and Other Land Use sectors remain the largest source of GHG emissions, but transport becomes comparably more important in terms of its contribution to total GHG emissions after implementation of all ten mitigation measures (Fig. 1).

For individual GHGs, carbon dioxide emissions are reduced only by 19 % (Table 6), but the mitigation actions predominantly in agriculture lead to larger reductions in national total methane emissions, 27 % in 2030 compared to the baseline scenario. Co-emitted SLCPs and air pollutants, like black carbon, and fine particulate matter emissions are reduced to a substantially greater extent, with a 78 % reduction in black carbon emissions in 2030 compared to the baseline scenario. As outlined in Section 3.1, the major sources of these co-emitted SLCPs and air pollutants is the residential sector, and charcoal production and therefore the majority of their reduction is due the implementation of measures that switch households to cooking using cleaner fuels (e.g. electricity or LPG) or to more efficient biomass stoves. Therefore, it is this measure in the residential sector which results in the largest reduction in particulate matter air pollutant emissions. Other air pollutants, such as NO_x emissions are not reduced as substantially as other pollutants, as they are emitted from a wider variety of sources, which are not reduced to the same extent as emissions from the residential sector (in particular emissions from transport).

There are larger proportional reductions in GHG, SLCP and air pollutant emissions outside of Grand Lomé than in Grand Lomé. For GHGs, this reflects that measures in the forestry sector are implemented mainly outside of Grand Lomé. For SLCPs and air pollutants, it reflects that the measures which results in the largest reductions in black carbon and other particulate air pollutants, cleaner fuels for cooking, predominantly results in emission reductions outside Grand Lomé because of the larger fraction of the population cooking using wood and other biomass outside Grand Lomé currently.

Table 6
Sectoral reductions in GHGs in 2030 compared to a baseline scenario (million tonnes CO_2-eq) and reduction in national total emissions of individual pollutants (thousand metric tonnes).

	2018	2030 Baseline	2030 mitigation	2030 % reduction
Sectors (GHG emissions)				
Energy	6.5	13.3	11.0	16.8
Industrial processes	1.9	3.2	3.2	1.9
Agriculture	1.7	2.3	1.5	33.5
Forestry	10.1	11.2	8.1	27.4
Waste	0.2	0.4	0.4	0.0
Total	20.5 (16.3–24.8)	30.3 (24.0–36.6)	24.2 (19.2–29.2)	20.1
Pollutants				
Carbon dioxide	17,127 (13,050-21,203)	26,054 (19,853-32,256)	20,999 (16,000-25,998)	19.4
Carbon monoxide	470 (363–753)	800.9 (619–1283)	618.6 (478–991)	22.8
Methane	77.7 (64–93)	105.1 (87.1–126.3)	76.3 (63.3–91.7)	27.4
Non methane volatile organic compounds	47.5 (32–106)	83.5 (57.0–187.3)	62.8 (42.9–140.8)	24.8
Nitrogen oxides	26.1 (22.6–34.2)	46.1 (39.9–60.3)	32.0 27.7–41.9)	30.7
Nitrous oxide	1.1 (0.92–1.42)	1.6 (1.3–2.1)	0.9 (0.8–1.2)	44.5
Sulphur dioxide	6.8 (4.7–9.0)	11.9 (8.1–15.7)	7.4 (5.0–9.8)	37.8
Ammonia	4.2 (3.2–7.3)	5.8 (4.5–10.1)	2.9 (2.2–5.1)	49.4
PM_{10}	41.8 (32.9–59.1)	54.1 (42.6–76.4)	25.6 (20.1–36.2)	52.8
$PM_{2.5}$	37.0 (29.1–52.1)	47.7 (37.5–67.3)	21.4 16.8–30.2)	55.2
Black carbon	8.6 (6.4–11.0)	9.5 (7.1–12.1)	2.1 (1.6–2.7)	78.0
Organic carbon	13.2 (9.7–20.2)	17.1 (12.5–26.2)	8.1 (5.9–12.4)	52.8

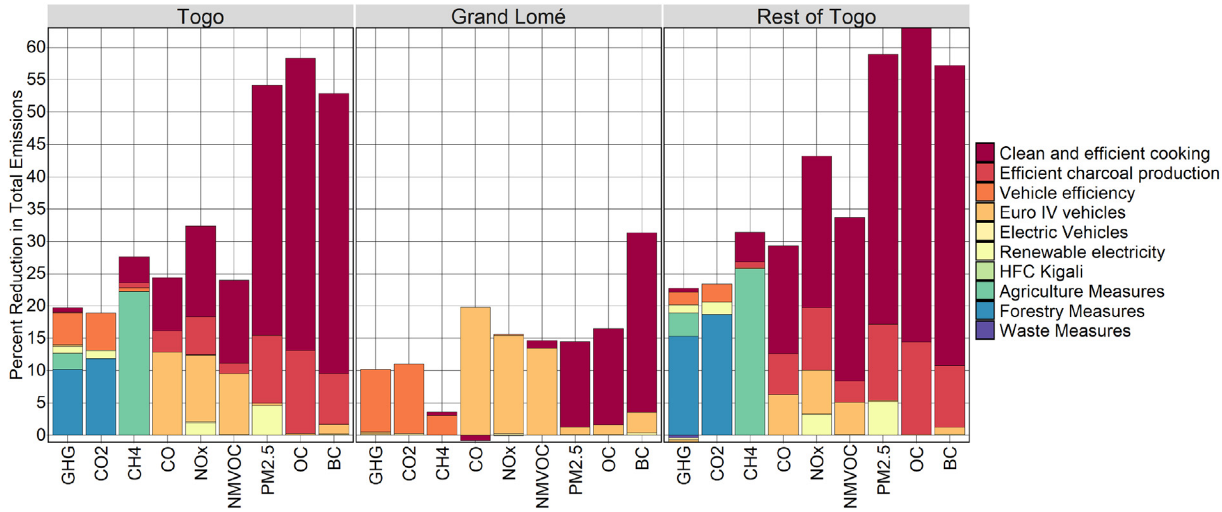

Fig. 4. Percentage reduction in total Greenhouse Gas, Short-Lived Climate Pollutant and air pollutant emissions in Togo, Grand Lomé and the rest of Togo from implementation of the 10 mitigation measures included in this assessment. The percentage reduction is disaggregated into the contribution from each mitigation measure.

4. Discussion

4.1. Implications for climate change and air pollution in Togo

Over the last decade, Togo has developed multiple plans and strategies related to reducing emissions to the atmosphere. Togo's first Nationally Determined Contribution committed to reducing GHG emissions by 11 % unconditionally, and up to 30 % in 2030 compared to a baseline scenario with international support (Togolese Republic, 2015). In 2021 Togo's updated NDC committed to a higher, 20.5 %, unconditional reduction in GHG emissions by 2030 compared to a baseline scenario, and up to a 50.57 % reduction in GHG emissions with international support (Togolese Republic, 2021a). In 2020, Togo published its National Action Plan to Reduce Air Pollutants and Short-Lived Climate Pollutants including mitigation measures that specifically target air pollutants and SLCPs (Togo Ministry of Environment, 2020).

This work presents for the first time an integrated assessment of the effectiveness of different mitigation measures in simultaneously reducing GHGs, SLCPs and air pollutants and their contribution to achieving Togo's plans for air pollution and climate change mitigation. The emission inventory developed for different pollutants highlights the substantial overlap in the major sources contributing to climate change and air pollution in Togo. For example, the transport sector contributes 30 % of carbon dioxide emissions in Togo, as well as almost half the nitrogen dioxide emissions. In terms of climate change mitigation ambition, the ten mitigation measures evaluated in this study result in a 20 % reduction in GHG emissions in 2030 compared to the baseline scenario. Therefore, these actions provide a robust basis for Togo's updated unconditional climate change mitigation commitment included in Togo's updated NDC. However, to achieve the conditional contribution, and to reduce Togo's GHG emissions by 50 % in 2030 compared to the baseline scenario, an additional set of mitigation measures, or the more ambitious implementation of those measures included in this study, is necessary. The largest reduction from the mitigation measures included in this study result from actions in the forestry sector, which reduce GHG emissions by 10 % and account for two-thirds of the GHG emission reduction potential of the mitigation measures evaluated in this study. Therefore, a key component of achieving Togo's climate change mitigation ambition is reducing net carbon dioxide emissions from forestry and other land use.

The specific measures included in this mitigation assessment to reduce net CO_2 emissions from forestland include reforestation, i.e. increasing by 5 % the land converted from other land to forest land by 2030, and reducing the forest land area burned in forest fires. The final measure included in the forestry sector was the implementation of actions that reduce demand for wood and charcoal for cooking in the residential sector. Residential cooking and charcoal production are the two largest sources of $PM_{2.5}$ emissions in Togo. The implementation of measures to switch to more efficient biomass stoves and cooking using cleaner fuels such as LPG and electricity are the measures that had the largest impact on reducing air pollutant emissions of the mitigation measures evaluated within this mitigation assessment. Implementation of these measures reduced $PM_{2.5}$ emissions by 41 % in 2030 compared to the baseline scenario. This achieves air pollution and health benefits in two ways. First it contributes to reductions in ambient $PM_{2.5}$ exposure, as for other sources of air pollutant emissions. It also contributes to reductions in household air pollution exposure, which is most directly associated with burning solid biomass fuels for cooking, and is responsible for the largest fraction of the air pollution health burden in Togo (Murray et al., 2020). It also disproportionately affects women and girls, who spend the largest fraction of time cooking (Clancy et al., 2012). Therefore, as a strategy that can achieve multiple benefits for air pollution and climate change, this mitigation assessment indicates that actions to reduce the number of households cooking using low efficiency biomass stoves is the most effective action evaluated, because of the resultant effect both on the direct air pollutant emissions from the residential sector, and the indirect impact on woodfuel losses from Togo's forest.

Once all ten of the mitigation measures included in this study have been implemented, the mitigation assessment identifies that the transport and forestry sectors are the largest sources of GHG emissions. In the transport sector, the mitigation measures include both an increase in efficiency of the vehicle fleet electromobility and vehicle emission standards. Therefore, to increase the GHG mitigation potential in the transport sector, an increase in the ambition of these measures could increase the overall GHG mitigation potential for Togo. For example, only 1 % of vehicles were estimated to be electric in the mitigation scenario due to the substantial technological and economic barriers to increasing electric vehicles in Togo's fleet. In addition, measures to promote public transport, particularly in Grand Lomé, where the majority of GHG emissions from transport were estimated to occur, could also reduce GHG emissions from transport.

While the mitigation assessment highlights that there are multiple actions that could simultaneously reduce GHG and air pollutant emissions at the national scale, it also highlights a necessity for different strategies to improve air quality in Grand Lomé compared to the rest of Togo. The sources of air pollutant emissions in Grand Lomé are dominated by the transport sector for gaseous air pollutants, and residential, commercial and public services and waste burning for particulate matter. Outside of Grand Lomé, residential biomass use, and charcoal production, are the largest air pollutant emission sources. Hence the difference in major emission sources means that different mitigation measures are more effective at reducing air pollutant emissions in Grand Lomé compared to the rest of

Togo. The implementation of vehicle emission standards (e.g. Euro standards) to progressively reduce the emissions from the fleet as it is renewed results in larger reductions in air pollutant emissions in Grand Lomé compared to the rest of Togo. Conversely the implementation of clean fuels and more efficient biomass stoves reduces air pollutant emissions in the rest of Togo to a greater extent than in Grand Lomé. However, some of the reduction in air pollutant emissions reduced in the rest of Togo are the result of households in Lomé switching to cooking using cleaner and more efficient stoves. In 2018, 82 % of charcoal consumed in the residential sector in Togo was consumed in Grand Lomé (Table 5), and therefore switching to cleaner and more efficient fuels for cooking in Grand Lomé could make a substantial contribution to reducing air pollutant emissions and ambient air pollution exposure in the rest of Togo.

Finally, this work has focused on the assessment of integrated action to mitigate climate change and improve air quality in Togo. Air pollution is only one human health and development priority that could be achieved by the measures identified to achieve Togo's climate change mitigation targets. Haines et al. (2017) reviewed many of the mitigation measures included within this assessment to identify their synergies, and potential tradeoffs, with different Sustainable Development Goals (SDGs). For the key mitigation measures that achieve climate change mitigation and air quality improvements, additional development priorities that could be achieved from the implementation of these measures include those related to eradicating poverty, energy access and sustainability, and protecting and enhancing biodiversity.

4.2. Comparison to previous studies, key uncertainties and future priorities to improve GHG quantification and mitigation assessment

There is uncertainty in the estimates of GHG, SLCP and air pollutant emissions resulting from the activity data used to represent key emitting source sectors, assumptions used to project these activity variables into the future for baseline and mitigation scenarios, and in the emission factors used to estimate emissions from a given level of activity in a particular sector. While there are no direct measurements of national total GHG, SLCP or air pollutant emissions to compare the emission totals estimated in this work, previous national and international assessments have also estimated historic GHG, SLCP and air pollutant emissions for Togo. Comparison of the emissions estimated quantified in this work to previous studies show broad consistency in the magnitude of historical GHG, SLCP and air pollutant emissions, with some exceptions.

National assessments of emissions in Togo to date have only quantified historical GHG emissions, and not included SLCPs like black carbon or other air pollutants. For GHGs, Togo's most recent national GHG emission inventory submitted to the UNFCCC estimates 20.4 million tonnes carbon dioxide emissions in 2018, and 128.3 million tonnes of methane (Togolese Republic, 2021c; Togolese Republic, 2021b). In comparison, the national total emissions of GHGs estimated in this study for 2018 are lower, by 14 % for carbon dioxide and by 40 % for methane. Carbon dioxide emissions are within the 95 % uncertainty range estimated for national total emissions, but the 40 % different in methane emissions is outside the 95 % uncertainty range, based on the aggregation of emission factor uncertainties (Table 5). Methane emission estimates are comparable for key methane emitting sources such as livestock and waste. The difference in methane emissions is due almost entirely to larger methane emissions estimated for biomass burning in the agriculture sector, where the national GHG inventory estimates 45.6 thousand tonnes methane emissions, making it the largest methane source, compared to 5 thousand tonnes in this study, which is more consistent with the relative contribution of different agricultural sources (livestock vs crop burning) to methane emissions from international assessments (Crippa et al., 2021). For air pollutants, studies using international databases have estimated air pollutant emissions in Togo. The results from this study on historical air pollutant emissions were generally consistent with those from international emission inventories. For example, national total $PM_{2.5}$ emissions for Togo in 2015 from the EDGAR emission inventory database were 37 thousand tonnes (Crippa et al., 2021; Crippa et al., 2018), compared to 36 thousand tonnes in this study (Table 5), with the majority from the residential sector. Nitrogen oxides emissions in were also comparable in 2015, 22.4 thousand tonnes in EDGAR, compared to 22.9 thousand tonnes in this study, with the largest contribution from the road transport sector. This indicates that the assessment of historical SLCP and air pollutant emissions using national data in this study is comparable compared to available existing air pollutant emission estimates developed for all countries using international data.

The quantitative assessment of uncertainties in the emissions of GHGs, SLCPs and air pollutants estimated in this study was undertaken based on the 95 % confidence intervals in the emission factors used in the emission assessment. The aggregated, 95 % uncertainty range for the national total emissions, shown in Table 5, indicates that there is smaller uncertainty in the emissions of GHGs in Togo compared to emissions of air pollutants. For carbon dioxide, there is relatively small uncertainty in the fuel combustion emission factors (95 % C.I.: $\sim \pm 5$ %, IPCC (2006)), and the largest component of the uncertainty in national total emissions results from uncertainty in the Forestry and Other Land Use net-CO_2 emissions. The air pollutants with larger 95 % uncertainty ranges include non-methane volatile organic compounds, carbon monoxide, and particulate matter air pollutants. The reason for the larger uncertainty ranges in these air pollutants is due to the large contribution of the residential sector to national total emissions, and the relatively larger uncertainty ranges in the emission factors used in this sector (EMEP/EEA, 2019). The measurement of country-specific emission factors for Togo for the residential sector could therefore result in substantial improvements to the accuracy and precision of Togo's national air pollutant emission estimates, which are the largest source of uncertainty in the national GHG, SLCP and air pollutant emission inventory.

As outlined in Section 2, the aim of this work was to estimate the GHG, SLCP and air pollutant emissions for different representations of Togo's major emitting sources. Therefore, the quantitative uncertainty assessment was undertaken based on the emission factor uncertainty. However, the activity data used represent each of Togo's emitting sectors, the modelling methods within which the activity data are used, and the assumptions about how these emission sources will change could also result in systematic and random uncertainty within the emission results, and emission reduction potential of mitigation measures. There is therefore substantial scope to improve the national assessment of GHG, SLCP and air pollutant emissions through improvement in the robustness of activity data, and the application of more detailed modelling methods for key sources.

The mitigation assessment for Togo relied on the availability of activity data to quantify emissions from all major source sectors, as well as assumptions about how Togo will develop into the future, and the consequences for emissions. Through its climate change reporting to the UNFCCC over the last two decades, Togo has progressively improved the availability and robustness of activity data from all major sources. The mitigation assessment presented in this work has benefited from previous efforts to improve data collection, and quality control (Togo Ministry of Environment, 2020; Togolese Republic, 2021b, 2021c). However, there remain uncertainties and areas where activity data and projection assumptions could be improved to create a more robust, detailed assessment of emission reductions from all major sources. The updating of this work as new activity data and projection assumptions become available could facilitate the progressive improvement of emission reduction assessments in Togo, and more effective monitoring of the implementation of the actions included in this work and identified as priorities in Togo's climate change and air pollution plans. Key uncertainties and potential future improvements are outlined below for each major emitting source sector.

In the energy sector, the national energy balance provided robust activity data over a long time series to estimate emissions for this sector (MME/DGE, 2018). This data is also updated regularly, facilitating periodic emission updates. However, in some energy sub-sectors, particularly industry and commercial and public services, the underlying energy consumption activity data did not include any information about the contribution of particular sub-sectors, activities or technologies that consume different types of fuel and electricity. The key limitation of the modelling methods for these energy sub-sectors was in the ability to assess detailed mitigation measures applied in industrial or services sub-sectors. Therefore, the mitigation measures modelled in these sectors included aggregate energy efficiency targets from national energy audits. A future improvement to the GHG mitigation assessment would be the development of a bottom-up characterisation of energy consumption in industry, commercial and public services, and the residential sector (outside of cooking), characterising the activities, technologies and subsectors consuming different fuels. A more detailed representation of these sectors would allow technology and sub-sector specific energy efficiency, or technological changes to be modelled which were not included in this assessment. This would require additional data collection on sub-sectoral energy consumption.

In the IPPU sector, one limitation is the lack of data on HFC imports before 2013, meaning that HFC emissions associated with equipment in use currently, but imported before 2013, are not considered. This will result in a systematic underestimate in the HFC emission estimates that will persist until 2027 (based on the IPCC (2006) Tier 1 assumption that HFC-containing equipment operates for 15 years before retirement). The HFC imported before 2013 is likely to be a small fraction of the in use HFC bank in Togo currently, and this limitation will become even less important in the future, as HFC in equipment imported before 2013 will constitute a smaller fraction of the HFC bank. However, this underlines the importance of continuing to collect data annually on HFC imports.

In the agriculture sector, IPCC Tier 1 methods were implemented to estimate emissions from livestock and crop production sources. There is a systematic uncertainty in the agriculture sector emissions resulting from a lack of data for inclusion of all GHG, SLCP and air pollutant emitting sources in Togo. For example, for inorganic fertiliser application, only nitrous oxide emissions were estimated, and other pollutants (ammonia, and nitrogen oxide) were not quantified. Nitrous oxide emissions were only estimated for urea application, due to a lack of data on the application of other inorganic fertilisers.

For livestock production, the IPCC (2006) methods multiply the total number of animals by an (default) emission factor. The key uncertainty and limitation of this application of the IPCC (2006) Tier 1 methodology is the aggregated way in which key parameters to reduce GHG, SLCP and air pollutant emissions from livestock are represented. This affects the detail with which the mitigation options in the agriculture sector could be represented. Key mitigation options to reduce emissions from livestock in Togo in an aggregate way, representing on farm measures like improved breeding, feed optimisation, as well as off-farm measures such as reducing food waste or dietary changes by specifying overall percentage changes in emissions from the livestock sub-sectors (Table 3). To assess the emission reduction potential of these measures, more detailed methodologies are required that allow key parameters, such as herd characteristics (feed composition, weights, fertility and mortality rates etc.) to be included in the modelling of GHG emissions. Therefore, a key improvement to Togo's agricultural GHG mitigation assessment would be the collection of data and development of an IPCC Tier 2 method model for agricultural GHG emissions (FAO, 2018; Malley et al., 2021a).

As outlined in Section 2.2.4, the key limitation of the Forestry and Other Land Use historical GHG emission estimate is the limited number of years for which land area data is available (1995, 2000, 2015 and 2018). This meant that annual land use conversions were average changes over years in between these data points, and which were then extended into the future for baseline scenario. The inclusion of data from additional years, and particularly more recent historical years, would allow for a more precise allocation of the overall 1995–2018 land use conversion to smaller time periods within this time series. This could also result in a more realistic baseline scenario projections. In addition, with the Forestry and Other Land Use Change sector, net-CO_2 emissions were only estimated for changes in biomass stocks in each land use category, and for land changing land-use category. Other sources and sinks of CO_2 from Forestry and Other Land, including changes in soil carbon, crop and pasture land management practises were not included in the assessment.

Finally, there is a systematic underestimation of the emissions from the waste sector because emissions were calculated only for the urban population. The biggest improvement to the mitigation assessment in the waste sector is the extension of the methodologies applied to estimate emissions from urban MSW and wastewater to the rural population, so that all emissions from the waste sector are captured in the analysis. A lack of data on rural waste generation rates, waste composition, and the percentage of waste that is handled by different waste streams for solid waste, and the percentage of rural wastewater handled by different treatment types, prevented the estimation of these emissions in this assessment. The collection of this data would allow future updates to the GHG mitigation assessment to capture a comprehensive estimate of MSW and wastewater emissions. The non-inclusion of the rural population is likely to not result in substantial changes to historic GHG emissions from solid and liquid waste, due to lower waste generation rates, and a lack of formal collection/wastewater treatment resulting in lower methane formation potential. However, it could have a larger impact on future emission projections, and emission reduction potential, if the future scenarios reflect rural development that includes formal waste collection and disposal, and wastewater management (e.g. through septic tank systems).

5. Conclusions

This work presents the first integrated assessment of Greenhouse Gas, Short-Lived Climate Pollutant and air pollutant mitigation in Togo. The assessment shows the large overlap in the major emission sources of those gases and particles contributing to both climate change and degraded air quality in Togo, providing a substantial opportunity to design integrated strategies that simultaneously improve air quality and mitigate climate change. This work shows that implementation of Togo's Nationally Determined Contribution (NDC) to mitigate climate change would achieve substantial simultaneous reductions in air pollutant emissions. The implementation of ten mitigation measures from Togo's updated Nationally Determined Contribution and National Action Plan to reduce air pollutants and SLCPs were evaluated. The assessment showed that fully implementing these two plans would reduce GHG emissions by 20 % in 2030 compared to a baseline scenario, and lead to between 25 % and 78 % reductions in emissions of various health-damaging air pollutants. Key to achieving these multiple benefits for climate change mitigation, air pollution and human health is action to transition to cleaner fuels (e.g. LPG, electricity) and more efficient biomass stoves for cooking in the residential sector. This sector makes the largest contribution to air pollutant emissions in Togo, and therefore switching to cleaner and more efficient practises would reduce household air pollution exposure, and emissions from the largest sources contributing to ambient air pollution. At the same time, measures in this sector were also shown in this assessment to contribute to reductions in deforestation and land degradation, which led to the largest reduction in GHGs of all mitigation measures evaluated.

Finally, the development of this first integrated air pollution and climate change mitigation assessment provides the basis for future routine updates to the mitigation assessment. This can facilitate monitoring of implementation of the mitigation measures included in Togo's climate change and air pollution plans and strategies, updating and evaluation of additional mitigation measures, e.g. to increase climate change mitigation ambition or to reflect changes in socioeconomic development or major GHG and air pollutant sources.

CRediT authorship contribution statement

Akpe Agbossou: Conceptualisation, Methodology, Formal Analysis, Writing – Original Draft, Jérémie Kokou Fontodji: Conceptualisation, Methodology, Formal Analysis, Writing – Original Draft Koffi Ayassou: Methodology, Formal Analysis, Writing – Reviewing and Editing Sanonka Tchegueni: Methodology, Formal Analysis, Writing – Reviewing and Editing, Kossi Novinyo Segla: Methodology, Formal Analysis, Writing – Reviewing and Editing, Kossi Adjonou: Methodology, Formal Analysis, Writing – Reviewing and Editing, Yao Bokovi: Methodology, Formal Analysis, Writing – Reviewing and Editing, Ayite-Lo Ajayon: Methodology, Formal Analysis, Writing – Reviewing and Editing, Aniko Polo-Akpisso: Methodology, Formal Analysis, Writing – Reviewing and Editing, Project Administration, Johan C.I. Kuylenstierna: Methodology, Formal Analysis, Writing – Reviewing and Editing, Christopher S. Malley: Conceptualisation, Methodology, Formal Analysis, Writing – Original Draft, Eleni Michalopoulou: Methodology, Formal Analysis, Writing – Reviewing and Editing, Jessica Slater: Methodology, Formal Analysis, Writing – Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary

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