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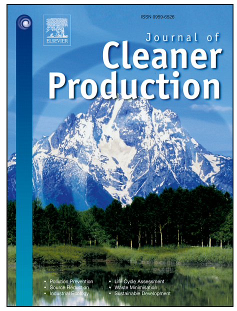

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Modelling future patterns of urbanization, residential energy use and greenhouse gas emissions in Dar es Salaam with the Shared Socio-Economic Pathways

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Abstract

This paper presents three scenarios of urban growth, energy use and greenhouse gas (GHG) emissions in Dar es Salaam using narratives that are consistent with the Shared Socio-Economic Pathways (SSPs). We estimate residential energy demand and GHG emissions from 2015 to 2050 for household activities (including upstream electricity generation) and passenger (road) transport (Scopes 1 and 2). We project that by 2050, Dar es Salaam's total residential emissions would increase from 1,400 ktCO_2e (in 2015) up to 25,000 – 33,000 ktCO_2e (SSP1); 11,000 – 19,000 ktCO_2e (SSP2); and 5,700 – 11,000 ktCO_2e (SSP3), with ranges corresponding to different assumptions about household size. This correlates with an increase in per capita emissions from 0.2 tCO_2e in 2015 to 1.5 – 2 tCO_2e (SSP1); 0.7 – 1.3 tCO_2e (SSP2); and 0.5 – 0.9 tCO_2e (SSP3). Higher emissions in SSP1 (the sustainability scenario) are driven by a higher urban population in 2050 and increased energy access and electricity consumption. Through aggressive GHG mitigation policies focused on decarbonization of the electricity sector and road transport, total emissions under SSP1 can be reduced by ~66% in 2050. Study insights aim to inform policies that identify and capture synergies between low-GHG investments and broader socio-economic development goals in Sub-Saharan African cities.

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Nomenclature

BRT – Bus Rapid Transit

GDP – Gross Domestic Product

GHG – Greenhouse Gas

HDI – Human Development Index

IAM – Integrated Assessment Model

IEA – International Energy Agency

INDC – Intended Nationally Determined Contribution

IPCC – Intergovernmental Panel on Climate Change

LEAP – Long-Range Energy Alternatives Planning Software

LPG – Liquified Petroleum Gas

LULUCF – Land Use Land-Use Change and Forestry

SDGs – Sustainable Development Goals

SSA – Sub-Saharan Africa

SSPs – Shared Socio-Economic Pathways

UN – United Nations

UNFCCC – United Nations Framework Convention on Climate Change

WHO – World Health Organization

<u>Metrics</u>

HH – Household

km – kilometer

$ktCO_2e$ – kilotonnes of carbon dioxide equivalents

kWh – kilowatt hour

GJ – Gigajoules

USD $ – United States Dollar

yr – year

Equations

***Year* –** year of prediction

TP_{Year} **–** Tanzania's total population (in millions) for a given year

TUP_{Year} **–** Tanzania's urban population level (as a percentage) for a given year

PS_{Year} **–** Population share of Dar es Salaam (as a percentage of the total urban population) for a given year

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1. Introduction

How emerging Global South cities – especially in the Sub-Saharan Africa (SSA) region – mitigate and adapt to climate change is critical to future sustainability. By the end of the century, over 30 SSA cities are expected to be among the world's largest megacities (with populations exceeding 10 million) (Hoornweg and Pope, 2017) compared to two megacities in 2017 (Lagos and Kinshasa) (WorldAtlas, 2017; UN, 2018). Though the region accounts for only 3.7% of global energy-related greenhouse gas (GHG) emissions (IEA, 2019), rapid urbanization and economic growth will increase future energy demand and GHG emissions. The growth of new urban infrastructure, such as power plants, roads, water supply and sewer systems, will push the region's aggregate material and energy use to much higher levels (Westphal *et al.*, 2017). Urban sprawl, and persistent decline in urban population density, will be an additional driver of energy demand and emissions (Angel *et al.*, 2011). Therefore, steering SSA cities towards a low-GHG future is critical to energy policy and planning (Godfrey and Xiao, 2015) as urban growth will impact global emissions due to the projected expansion of Africa's population (Calvin *et al.*, 2016). However, literature on the future energy and GHG emissions transitions of SSA cities is limited to a few studies (e.g., Godfrey and Xiao (2015) and SEA (2015a)). This calls for research that investigates different scenarios of urban growth and energy use in SSA cities, and specifically, identifies key sectors (e.g., residential, transportation and industrial) driving these changes within individual cities.

There are two main contributions of this paper. To our knowledge, we present the first projections of possible changes in residential energy use and GHG emissions, i.e., from domestic activities, including household and transportation activities, in Dar es Salaam, Tanzania (one of the largest and fastest growing cities in the SSA region (Hoornweg and Pope, 2017)). Our analysis highlights the household and transportation drivers that are the primary contributors to future GHG emissions in Dar es Salaam, providing insights for policy makers and urban planners. The projections are to 2050 and use the Shared Socio-Economic Pathways (SSPs) as a guiding narrative. The SSPs (further detailed in Section 2) were originally established by the climate change research community to facilitate integrated analysis of future climate impacts, vulnerabilities, adaptation and mitigation (Riahi *et al.*, 2017). There have been only a few applications of the SSPs at the city-level (e.g., Kamei *et al.* (2016) and Hoornweg and Pope (2017)), and none for the purpose of projecting GHG emissions and energy use in Dar es Salaam or any other major African city. Second, the paper presents a method for scoping GHG emissions pathways in a relatively data-poor environment, and demonstrates how the SSPs can be used to develop urban growth scenarios. Current urban energy use and/or GHG emissions studies tend to focus on Global North cities (where data sources and methods are more robust), despite calls to action for research attention and focus on the Global South (especially the SSA region) (IPCC, 2014; van der Zwaan *et al.*, 2018). The lack of research is further reflected by the few "urban metabolism" studies estimating the energy and GHG emissions flows in cities in the SSA region (e.g., Kampala (Lwasa, 2017), Lagos (Kennedy *et al.*, 2015) and Cape Town (Hoekman and von Blottnitz, 2017), among others). We focus here on cities as their spatial form and economy drives much of the national energy demand. However, these studies do not discuss expected changes in future GHG emissions in the manner presented in this paper. Our results show the wide uncertainty in these future projections, while simultaneously demonstrating the order of magnitude jump in emissions that can be expected in Dar es Salaam even under optimistic scenarios.

We focus on the residential sector as it is a dominant "end-use" sector in the SSA region (IEA, 2014, 2019). Regional estimates indicate that 66% of final energy use occurs in the residential sector, compared to 21% in the industrial, agricultural and services sectors (IEA, 2014). Similarly, in other large SSA cities such as Lagos and Accra, emissions from residential buildings (not including biomass use) were estimated at ~30% (2015) and ~23% (2015), respectively, of total stationery and transport emissions, compared to ~14% and ~5% in the case of industry (i.e., manufacturing and construction) (C40 Cities, 2017). Furthermore, while there is no available estimate of residential GHG emissions in Dar es Salaam (outside of the ones generated within this research), national GHG inventories estimate that electricity production and transportation (including for residential use) accounted for ~38% of Tanzania's total energy sector emissions (in 2014), compared to ~7% for industry (WRI, 2015). GHG emissions from industry would generally vary on a case-by-case basis and/or may be linked to specific regulations, and therefore emissions projections for industry would scale differently compared to residential emissions. For the above reasons, the focus of this paper is on residential activities, although industrial activities could be incorporated in future work.

To accomplish the contributions outlined above, this paper:

(1) Estimates the current (2015) emissions in Dar es Salaam, and present narratives (based on the SSPs) that project future changes in GHG emissions from domestic households, including public and private vehicle travel (Scopes 1 and 2) between 2015 and 2050;
(2) Assesses which household and transportation activities are the primary contributors to emissions to 2050;
(3) Analyzes how spatial factors such as urban population density influence energy use and GHG emissions; and,
(4) Provides actionable urban policy recommendations that can support a low-GHG and sustainable energy transition in Dar es Salaam, and the SSA region more broadly.

2. Literature review: Infrastructure and energy transitions in Africa and other Global South cities

The African Development Bank estimates the scale of investments required to build SSA's future infrastructure at between $130 and $170 billion a year (AfDB, 2018). This infrastructure demand presents a unique opportunity to build more sustainable (and resilient) cities with policies that promote low-GHG and resilient communities (that especially benefit the poor). However, the urbanization of SSA cities comes with unique challenges. Unlike the transformation in Europe and North American cities, whose urbanization was correlated with industrialization and economic growth (Currie and Musango, 2017), these associations are not evident in the SSA region (Allen, 2014). Rather, urban growth has been predominately "splintered" and reinforced by socio-economic challenges such as poverty, inequality and vulnerability to climate change (Allen, 2014; Currie and Musango, 2017). Splintered urbanism has heightened inequalities, as basic infrastructure services, such as electricity, water supply and public transportation, are often limited or non-existent for the poorest neighborhoods (Allen, 2014; Currie and Musango, 2017). In this regard, studies find that low levels of infrastructure stock (and urban wealth) in SSA cities is a key reason for their limited energy use and GHG emissions compared to higher-income cities (Kennedy *et al.*, 2015).

A handful of prior studies have compared electricity use, transportation emissions and/or direct final energy use among global cities (e.g., Schulz (2010); Grubler *et al.* (2013) and Kennedy *et al.* (2014)), and report values for Dar es Salaam (0.16 MWh/capita, ~1 tCO_2e/capita, 17GJ/capita) that are far lower than their counterparts in the U.S. (9 – 10 MWh/capita and 4 tCO_2e/capita) or Canada (162 GJ/capita in Toronto). Another set of studies quantify the flows of materials, energy, and waste in cities using urban metabolism frameworks. Metabolism assessments are available for a limited number of SSA cities, including Kampala (Lwasa, 2017), Durban (Jagarnath and Thambiran, 2018) and Cape Town (Hoekman and von Blottnitz, 2017). Increasing resource access remains a key challenge for these cities, with Kennedy *et al.* (2015) concluding that SSA cities (e.g., Lagos) are "consuming resources at rates below those that support a basic standard of living for all citizens". This is consistent with research comparing 120 African cities that found strong correlations between resource use and GDP/capita or Human Development Index (HDI) ratings (Currie *et al.*, 2015; Currie and Musango, 2017).

Few studies have projected energy use and GHG emissions pathways in SSA cities (e.g., Senatla (2011), Godfrey and Xiao (2015), SEA (2015a) and Stone and Wiswedel (2018)). However, there are a number of studies in other regions of the Global South, especially Asian and Latin American cities (e.g., McPherson and Karney (2014), Collaço *et al.* (2019) and Huang *et al.* (2019)). Emissions pathways are estimated using scenario-based models that aggregate data across different urban sectors. For example, Stone and Wiswedel (2018) use the Stockholm Environment Institute's Long-Range Energy Alternatives Planning (LEAP) software to assess the scale of GHG emissions growth (from residential, industrial and transport activities) in urban SSA from 2012 to 2040. Results indicate that urban energy demand in SSA cities could increase fourfold by 2040, with GHG emissions rising 280%. This would shift the region's share of global emissions from 1% (in 2012) to 4% in 2040. In China, Huang *et al.* (2019) also use LEAP to project peak levels of GHG emissions in the city of Guangzhou. Findings show that while emissions will peak by 2023 under existing climate mitigation policies, the peak could be moved forward to 2020 with more stringent energy conservation and policies, including (among other interventions): (1) adjusting the energy mix and mode of passenger transport; (2) and replacing coal and oil use with electricity and natural gas in the industrial sector; and, (3) enabling large scale-up of renewable energy power. Similar applications of the LEAP model at the city-level are available for São Paulo (Collaço *et al.*, 2019), Panama (McPherson and Karney, 2014), Bangkok (Phdungsilp, 2010), and several Chinese cities (Zhou *et al.*, 2016; Fan *et al.*, 2017; Yang *et al.*, 2017; Lin *et al.*, 2018), among others.

Outside of LEAP, researchers have employed models and frameworks designed for specific sectors, including buildings (e.g., Lin *et al.* (2017), Li *et al.* (2019) and Mokhtara *et al.* (2019)), transportation (e.g.,Pongthanaisawan and Sorapipatana (2013), Aggarwal and Jain (2016), Dhar *et al.* (2017) and Du *et al.* (2017)) and industry (e.g., Wang *et al.* (2013) and de Souza *et al.* (2018)). Other studies have used Integrated Assessment Models (IAMs) to forecast long-term energy and emissions scenarios (e.g., Riahi *et al.* (2017), van Sluisveld *et al.* (2018), Silva Herran *et al.* (2019) and Wu *et al.* (2019)). IAM literature remains limited in the SSA region, with notable exceptions by Calvin *et al.* (2016), Lucas *et al.* (2015) and van der Zwaan *et al.* (2018). In particular, van der Zwaan *et al.* (2018) model pathways for low-carbon development in Africa (including North African countries) using the “TIAM-ECN” IAM model, designed to simulate the development of energy economies over time. Their findings show that while Africa’s GHG emissions could become substantial at a global scale by 2050, the region could “leapfrog” fossil-fuel based growth with large-scale use of renewable energy options (van der Zwaan *et al.*, 2018).

A final set of studies couple IAMs with the SSPs to project a range of socio-economic trends, such as future changes in global population (KC and Lutz, 2017), urbanization (Jiang and O’Neill, 2017) , energy use (Bauer *et al.*, 2017) and air pollution (Rao *et al.*, 2017). However, a number of research gaps remain in the IAM and SSP literature. Local- or city-level data is not widely incorporated into models and there is need for additional research at lower geographic scales to enable local dynamics to be incorporated into IAMs (Cronin *et al.*, 2018). Currently, studies by Kamei *et al.* (2016) and Hoornweg and Pope (2017) are among the few studies that adopt the SSP narratives at the city-level (though, do not use an IAM approach). Kamei *et al.*

(2016) determine long-term socioeconomic scenarios in Tokyo based on a theoretical model and expert interviews, while Hoornweg and Pope (2017) couple their narratives with regression models to project urbanization trends in the world's largest cities to 2050, 2075 and 2100.

Gaps in modelling approaches remain, and researchers have called for additional studies in developing regions, especially Africa (Cronin *et al.*, 2018; van der Zwaan *et al.*, 2018). Our paper contributes to the growing SSP literature as well as provides the first application of SSPs in Dar es Salaam or Tanzania. The novelty in our approach is embedded in our scenarios and projections. Unlike existing urban metabolism studies conducted in the region that do not focus on changes in GHG emissions over time (e.g., Kampala (Lwasa, 2017), Lagos (Kennedy *et al.*, 2015), Durban (Jagarnath and Thambiran, 2018) and others aforementioned), we present current (2015) and potential changes in GHG emissions in Dar es Salaam to 2050, deriving insights that may inform GHG projections for other SSA cities. Furthermore, considering that the IAMs (including the SSPs) are not adapted for city level analysis (Cronin *et al.*, 2018), we couple our SSP narratives with a LEAP modelling approach (as LEAP has been widely adopted to estimate long-term energy use and GHG emissions in developing country contexts). Finally, while research by Grubler *et al.* (2013) and Kennedy *et al.* (2014, 2015) highlights the low energy use of SSA cities (compared to Global North cities), increasing economic activity in the region will cause the region's future emissions to become substantial at the global level (van der Zwaan *et al.*, 2018). However, cities have an opportunity to implement policies that support low-GHG communities and realize significant GHG mitigation with future urban growth. Therefore, the urbanization narratives modelled in this paper – SSP1 (Sustainable Growth), SSP2 (BAU Growth), and SSP3 (Fragmented Growth) (described in the Methods) – present distinct urbanization, energy use and GHG emissions futures for Dar es Salaam. The narratives provide a basis for identifying (1) key household and transportation drivers of GHG emissions in Dar es Salaam, and (2) investments that can support future emissions reductions (which could potentially be generalizable to other large SSA cities).

3. Case Study of Dar es Salaam, Tanzania

With an estimated population of 5.1 million (or ~1.3 million households) in 2015 (World Bank, 2018), Dar es Salaam is the largest city and economic hub of Tanzania. The city is experiencing significant changes in urban form, although it is noted that the city masterplan was last updated in 1979 (Government of Tanzania, 2017a). Structurally, Dar es Salaam exhibits a monocentric and radial urban form, with highest population densities clustered around the city centre and along the four major arterial roads, i.e., to the north along Bagamoyo road, north-west along Morogoro road, south-west along Nyerere road and south along Kilwa road (Figure 1).

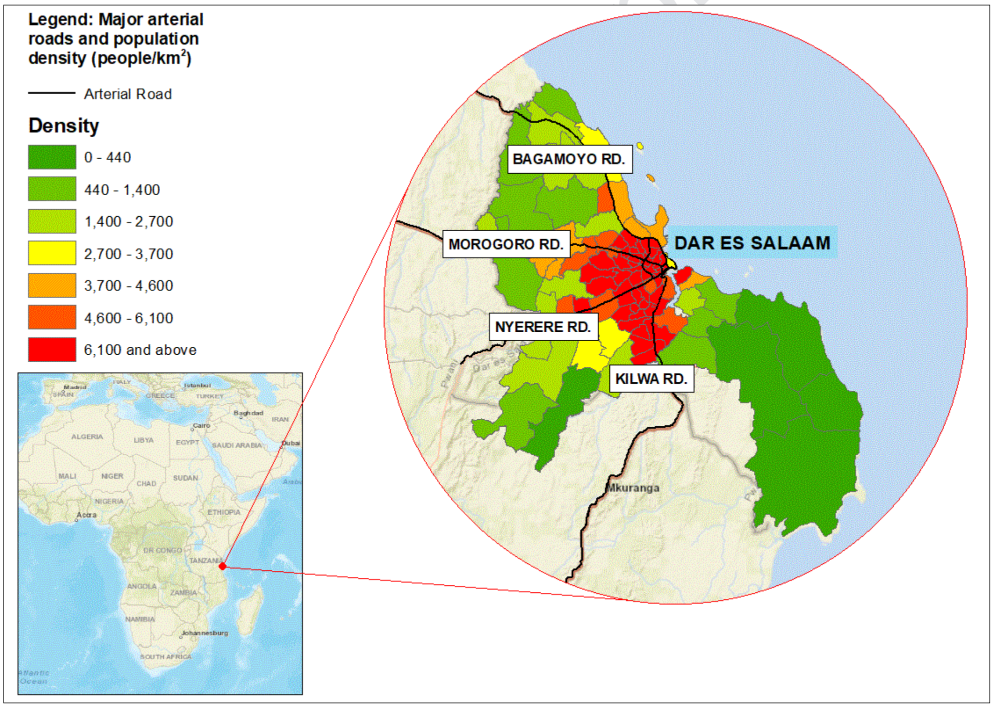

Figure 1: Map showing average population densities in Dar es Salam (by ward) and major arterial roads (Bagamoyo, Kilwa, Morogoro and Nyerere). Map was compiled in ArcGIS by authors using population data from the 2012 national census report. (Government of Tanzania, 2016b, 2017a)

Generally, energy sector statistics in Tanzania are reported at the national level, including through the National Communications to the United Nations Framework Convention on Climate Change (UNFCCC) (Government of Tanzania, 2015). An estimated 75% of Dar es Salaam households have access to electricity (DHS Program, 2016; Government of Tanzania, 2017b).

Despite high electrification levels compared to rural areas (Government of Tanzania, 2017b), urban households experience frequent power cuts and fluctuations in voltage that can damage electric appliances (Garside and Wood, 2018). To compensate for electricity shortages, “fuel stacking”, where households use a combination of other fuels such as wood, charcoal, liquefied petroleum gas (LPG) or kerosene (in addition to electricity) is widespread (Lusambo, 2016). It is estimated that only 2% of Dar es Salaam households use only electricity for cooking and heating needs (DHS Program, 2016).

In the transport sector, approximately 62% of all passenger trips (~81% of vehicle trips) are by small minibuses called “dala-dalas” (Mkalawa and Haixiao, 2014). Other modes include private cars (including taxis) (16% of vehicle trips) and motorcycles and tricycles (known locally as “bodas” and “bajajis”) (3% of vehicle of trips) (Table 2) (Mkalawa and Haixiao, 2014).The dala-dala service is widely used by the poor given its affordability, though it is often characterized by poor service quality, untrained bus operators and non-adherence to traffic rules and regulations (Nkurunziza *et al.*, 2012). To improve standards of service, the city is implementing a six-phase Bus Rapid Transit (BRT) system, with main corridors operating along the four major arterial roads (Figure 1) (Government of Tanzania, 2017a). Phase 1 of the BRT was completed in 2016 and operates along Morogoro road (Figure 1), which traverses from Dar es Salaam’s high-income central business district towards middle- and low-income residential areas in the west. Plans to expand the BRT up to six phases are currently underway (World Bank, 2017b). More detail about the BRT implementation is available in SM.9.

4. Methods

We model future pathways of energy use and GHG emissions in Dar es Salaam from 2015 (current year) to 2050 with a focus on the residential sector, including associated public and private road transportation. We include direct (Scope 1) emissions from households (i.e., emissions from the use of charcoal, wood, kerosene or liquified petroleum gas (LPG), and emissions from road travel using private vehicles or public transport modes), as well as upstream (Scope 2) emissions from electricity generation (for household use or electric vehicle charging). We broadly describe these activities as “residential” in the remainder of the paper. We do not account for emissions from fuel production, or from commercial and industrial activities, including air, railway or marine transport. We also do not include embodied (Scope 3) emissions associated with product manufacture and shipping.

The focus on residential energy use and emissions is due to the large contributions of these activities compared to industrial activities, or other productive sectors. Domestic use of biomass (i.e., charcoal and fuel wood) accounts for over 90% of final energy consumption in Tanzania (Government of Tanzania, 2014a). However, biogenic carbon emissions from biomass combustion, as well as emissions from Land Use Land-Use Change and Forestry (LULUCF) are not included in emissions inventories for the energy sector category. Emissions accounted for in the sector include national electricity (~11%), road transportation (~27%), manufacturing/construction (~7%), and commercial, residential and agricultural activities (~55%) (WRI, 2015).

All GHG emissions are stated in kilotonnes of carbon dioxide equivalent ($ktCO_2e$), which includes CO_2, methane and nitrous oxide. GHG emissions are calculated using 100-year global warming potentials (GWP) (IPCC, 2013). GWPs and emissions factors for all household and transport fuels are listed in SM.1.

4.1. Dar es Salaam's Urbanization Narratives

Our urbanization narratives are inspired by the SSPs which have been developed and modelled by climate change researchers (e.g., Riahi *et al.* (2017)). The original SSPs are based on five narratives or "storylines", each with different consequences for global and regional socio-economic development under increasing climate uncertainty (O'Neill *et al.*, 2017). We focus specifically on SSP1, SSP2 and SSP3 as they sufficiently illustrate a range of possible futures that encompass results from SSP4 ("Inequality") and SSP5 ("Fossil-Fueled Development").

The narratives presented in this paper are simplified baseline projections of Dar es Salaam's future energy use and GHG emissions. Each narrative is distinct and highlights different energy use dynamics and outcomes. We assume no additional climate mitigation actions beyond the baseline narratives (and as outlined in the Methods). Therefore, in Section 4.4, we include an additional mitigation scenario that facilitates the examination of aggressive GHG mitigation policies focused on decarbonization of electricity and road transportation, and assesses which activities have the potential to drive the largest emissions reductions to 2050. Table 1 describes Dar es Salaam's urbanization narratives and justifications, as appropriate.

Table 1: Dar es Salaam's Urbanization Narratives (inspired by the SSPs).

Indicators	SSP1 (Sustainable Growth)	SSP2 (Business as Usual Growth)	SSP3 (Fragmented Growth)
Population	▪ Fast initial population growth by 2050. ▪ Lowest peak in population after 2050 (Figure 2).	▪ Moderate population growth, consistent with historic growth trends. ▪ Moderate peak in population after 2050 (Figure 2).	▪ Slow initial population growth. ▪ Highest peak population after 2050 (Figure 2).
Households	▪ 100% electrification is realized by 2050, resulting in net-zero consumption of traditional fossil fuels (i.e., charcoal and wood) by 2050.	▪ 100% electrification by 2050, though households continue to rely on traditional fossil fuels.	▪ No change in electrification levels from 2015, and households continue to rely on traditional fossil fuels.
Passenger Transport	▪ Phases 1 to 4 of the BRT are complete by 2050. ▪ BRT ridership accounts for 40% of total passenger trips, similar to reported ridership in Latin American and Chinese cities (WRI, 2018). ▪ Fuel efficiency of light-duty vehicles (LDVs) improves to OECD levels, in line with global targets to 2050 (OECD/IEA, 2017a).	▪ Phases 1 to 4 of the BRT are complete by 2050. ▪ BRT ridership accounts for 15% of total passenger trips, consistent with existing BRT implementation plans (World Bank, 2017b). ▪ Fuel efficiency of LDVs progresses to the same levels observed in middle- and high-income cities today.	▪ Phases 1 to 4 of the BRT are complete by 2050. ▪ BRT ridership accounts for 15% of total passenger trips, with future BRT expansion plans halting post-2050. ▪ Fuel efficiency of LDVs progresses to the same levels observed in middle- and high-income cities today.

4.2. Modelling using the LEAP platform

For each SSP narrative, we use the LEAP modelling platform (Heaps, 2016) to calculate Dar es Salaam's residential energy use and GHG emissions to 2050. The platform offers a transparent way of structuring complex energy data, projecting different demand and supply scenarios, and integrating factors such as population growth, GDP and policy changes to energy sector analysis (Heaps, 2008, 2016). LEAP has not been employed to model energy use and GHG emissions in Dar es Salaam or Tanzania.

Modelling capabilities include built-in calculations to determine energy use and GHG emissions based on time-varying data points (Heaps, 2008, 2016). The platform's Technology and Energy Database includes GHG emissions data for a range of fuels based on the Intergovernmental Panel on Climate Change (IPCC) guidelines. The supplementary material (SM.10) provides more detail about the calculation structure within LEAP.

4.3. Data sources and underlying assumptions (2015 – 2050)

We estimate Dar es Salaam's residential energy use and GHG emissions using the following data and assumptions (see Table 2): (1) population, GDP and household size; (2) population density; (3) the GHG intensity of electrification; (4) fuel use at the household level; and (5) fuel use for road transportation. The following sections describe our approach in sourcing data. We also caveat that where data is not available for Dar es Salaam, we draw from national estimates, or proxy data from other cities in developing regions.

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Table 2: Key indicators and underlying assumptions for estimating Dar es Salaam's residential energy use and GHG emissions for SSP1 (Sustainable Growth), SSP2 (BAU Growth), and SSP3 (Fragmented Growth) narratives from 2015 to 2050.

#	Indicator	Unit	Current year – 2015	Data source for current year	SSP1 – 2050	SSP2 – 2050	SSP3 – 2050	Data source for assumptions to 2050
1	**Population**	million	5.1	(World Bank, 2018)	16	15	12	Equation 1
2	**GDP/Capita**	USD $	1,100	(IIASA, 2015)	4,700	2,500	1,500	(IIASA, 2015)
3	**Household (HH) size**	persons/HH	4	(Government of Tanzania, 2014b)	[2 – 4]	[2 – 4]	[2 – 4]	Reduction to 2 persons/HH at the lower bound reflects the lowest HH size observed globally today (UN, 2017)
4	**Number of households**	million	1.3	(Government of Tanzania, 2014b)	[4 – 12]	[4 – 8]	[3 – 6]	Author calculation
5	**Average population density**	persons/km^2	3,100	(Government of Tanzania, 2014b)	3,100	3,300	3,500	Downscaled 1km^2 population density projections from (Jones and O'Neill, 2016) (Figure 3).
6	**% change in average population density**				0%	6%	13%	
7	**Electrification level**	% of total households	75	(Government of Tanzania, 2017b)	100	100	75	(Government of Tanzania, 2017b)
8	**GHG intensity of electricity**	gCO_2e/kWh	405	Author calculation	405[3]	435[3]	435[3]	Author calculation
9	**Electricity use[1, 4]**	GJ/HH/yr.	5	(IEA, 2014)	46	25	18	Assumption based on SSP narratives for total household energy use; see Table 3.
10	**LPG use[1, 4]**		4	(Drazu *et al.*, 2015)	0	16	10	
11	**Kerosene use[1, 4]**		1		0	13	7	

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#	Indicator	Unit	Current year – 2015	Data source for current year	SSP1 – 2050	SSP2 – 2050	SSP3 – 2050	Data source for assumptions to 2050
12	**Fuelwood use**[1,4]		16	(Drazu *et al.*, 2015)	0	0	8	
13	**Charcoal use**[1,4]		21	(SEA, 2015b, 2015a)	0	0	10	
14	**Annual VKT per capita**	km	870	(Mkalawa and Haixiao, 2014; World Bank, 2017a)	870	860	840	Elasticity between density and VKT (Guerra, 2014)
15	**LDV**	% of total vehicle trips	16%	(Mkalawa and Haixiao 2014)	12%	15%	15%	Based on assumption that relative change in vehicle trips will mostly shift from dala-dala to BRT as stated in Methods, with small changes in LDV and motorcycle/tricycle use.
17	**Dala-dala** (standard bus: 40-seater)		81%		55%	67%	67%	
18	**Boda or Bajaji** (motorcycle or tricycle)		3%		3%	3%	3%	
16	**BRT**		0%[2]	(World Bank, 2017b)	30%	15%	15%	Based on projected completion of BRT Phases 1 to 4 (see (World Bank, 2017b))
19	**Electric Vehicles**[4]		0	(IEA, 2017a, 2018)	1%	0.1%	0.1%	(IEA, 2017a, 2018)
20	**Fuel use**[5] (LDV)	litres/100km	12	(World Bank, 2017a)	4.4	7.4	7.4	(IEA, 2014, 2017a)
21	**Fuel use**[5] (BRT)		38	(DART Agency, 2017)	No change.			Author assumption.

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#	Indicator	Unit	Current year – 2015	Data source for current year	SSP1 – 2050	SSP2 – 2050	SSP3 – 2050	Data source for assumptions to 2050
22	**Fuel use**[5] (dala-dala)		33					
23	**Fuel use**[5] (Boda or Bajaji)		1.8	(IEA/GFEI, 2015)				

Load factor by vehicle mode (from 2015 to 2050):

- LDVs – 1.8 passengers/vehicle (World Bank, 2017a)
- Dala-dala – 40 passengers/vehicle (DART Agency, 2017)
- BRT – 150 passengers/vehicle (DART Agency, 2017)
- Boda or Bajaji – 1.2 passengers/vehicle (World Bank, 2017a)

Notes:
[1]Total household energy use remains constant for all future projections, though the relative shares of fuel use change based on the SSP narrative.
[2]We assume no BRT ridership in 2015. Phase 1 of the BRT was fully operational in May 2016 (DART, 2017).
[3]We assume different changes in the generation mix depending on the scenario (SM.3)
[4]EV projections are based on current IEA estimates for South Africa (SSP2 and SSP3) and Europe (SSP1).
[5] 90%and 10% of LDVs in Tanzania use gasoline and diesel respectively (World Bank, 2017b). Taking into account these relative shares, average LDV fuel use is estimated, assuming ~7 (World Bank, 2017a).

4.3.1. Population, GDP and Household Size

For each SSP narrative, we estimate Dar es Salaam's future population to 2050 as follows:

$$\boldsymbol{DAR\ Population_{Year}} = \boldsymbol{TP_{Year}} \times \boldsymbol{TUP_{Year}} \times \boldsymbol{PS_{Year}} \qquad \textbf{(1)}$$

Where ***Year*** represents the year of prediction, ***TP*** represents Tanzania's total population (in millions) for the given year, ***TUP*** represents Tanzania's urban population level (as a percentage) for the given year, and ***PS*** is the population share of Dar es Salaam (as a percentage of the total urban population) for the given year.

We determine Tanzania's total population (***TP***) and urban population level (***TUP***) from the existing population and urbanization projections for the SSPs (Jiang and O'Neill, 2017; KC and Lutz, 2017), which include data from 2010 to 2100. Over the last 20 years, Dar es Salaam has consistently accounted for approximately 30% of the country's total urban population (World Bank, 2018). We assume this share will remain at 30% across all future scenarios (while a rate of 30% may seem low, we expect that this is consistent with the large growth also expected in other Tanzanian cities). Finally, we estimate GDP per capita between 2015 and 2050 by dividing Tanzania's projected GDP, available in the SSP database (IIASA, 2015), by Tanzania's projected total population (***TP***).

4.3.2. Household Size

We estimate the average household size in Dar es Salaam at four persons per household in 2015 (Table 2) (DHS Program, 2016). Across all SSPs, Tanzania's total fertility rate (TFR) is projected to fall (Lutz *et al.*, 2014), suggesting that household size will likely decrease in the future. To estimate future changes in household size and impact on household energy use and emissions, we consider two bounding scenarios – (1) as an upper estimate, we assume household size remains constant at four persons per household to 2050; and (2) as a lower estimate, we assume an eventual reduction in household size to 2 persons per household by 2050, consistent with the lowest household estimates observed globally today (UN, 2017). This also serves the purpose of allowing per capita energy to increase as a function decreasing household size. For example, our assumption that total household energy use remains constant to 2050 (Table 3), implicitly increases per capita energy use with the reduction in household size. Therefore, while we are unable to create a more refined estimate of changes in total household energy use in Dar es Salaam due to the data limitations, our modelling explores some possible futures in GHG emissions across a range of estimates (based on both constant and changing household size).

4.3.3. Population Density

We project Dar es Salaam's average population density using Jones and O'Neill's (2016) spatial projections which map global and regional changes in urban, rural and total population (based on 1km^2 grids) from 2010 to 2100. By considering only those grids that fall within Dar es Salaam's administrative boundary, we calculate changes in the city's urban density (i.e., sprawl or concentration) for each processed layer (for SSP1, SSP2 and SSP3).

4.3.4. Electricity Generation

Currently, Tanzania's electricity generation mix is dominated by natural gas (59%) (SM.3); hydro-power (35%), Heavy Fuel Oil (HFO) (5.7%) and biomass (0.3%) account for the remaining fractions (Government of Tanzania, 2017c). By 2040, Tanzania aims to expand the generation mix to include coal, solar, wind and geothermal sources (Government of Tanzania, 2016a). According to Tanzania's Intended Nationally Determined Contribution (INDC) (Government of Tanzania, 2015), geothermal potential is estimated at 5GW and hydropower at 4.7GW (though installed capacity is currently 0.6GW (Government of Tanzania, 2016a)). Our LEAP model assumes different transformations in the generation mix for each SSP narrative. SSP1 assumes a 10% penetration of renewable energy, consistent with the highest level of renewable energy penetration scenario ('Scenario 6') considered in Tanzania's National Power Plan (Government of Tanzania, 2016a). SSP2 and SSP3 assume a shift in the generation mix to natural gas (40%), hydro-power (20%), coal (35%), and 5% penetration of renewable energy (i.e., solar and wind sources) by 2050. These advancements are consistent with the preferred scenario envisioned under Tanzania's National Power Plan ("Scenario 2") (Government of Tanzania, 2016a).

4.3.5. <u>Household Activities</u>

We estimate energy use and GHG emissions associated with fuels used for space and water heating, cooking, lighting and appliance use within the city (Scope 1), as well as associated emissions from electricity generation (upstream) (Scope 2). In 2015, Dar es Salaam's household electricity use was estimated at 1,250 kWh/household (HH)/yr (~5 GJ/HH/year). This is consistent with the World Bank's "Tier-4" level of electricity access, where households use electricity for lighting and some medium-power appliances (e.g., television, radio, phone charger) (World Bank, 2015). By 2035, Tanzania plans to achieve a national electrification rate of 90% (Government of Tanzania, 2016a). Therefore, our modelling assumes that 100% electrification is realized for SSP1 and SSP2 by 2050. SSP3 assumes no progress is made, with electrification remaining at 75%.

In most households, charcoal or LPG are widely used in combination with electricity. For example, in 2015, 75% of households in Dar es Salaam used electricity and 69% used charcoal (DHS Program, 2016; Government of Tanzania, 2017b), meaning that some households were using both charcoal and electricity for daily needs. Other household fuels include LPG (14%), wood (6%) and kerosene (6%). We implicitly account for these fuel stacking behaviors by calculating the total household energy use (in GJ/HH/yr) and estimate the relative change in fuel use shares (i.e., charcoal, wood, LPG and kerosene) for each SSP narrative (Table 3). Moreover, all future scenarios assume that total household energy use remains constant, though we change both the household size and the relative energy use shares from the different fuel sources based on the SSP narrative. Although household energy use remains constant, we report results in each scenario for both constant and decreasing household sizes, with the latter implicitly allowing growth in household energy use per person. Refining these projections for household energy use is an important area for future work.

Table 3: Modelling assumptions for changes in household energy use for (Sustainable Growth), SSP2 (BAU Growth), and SSP3 (Fragmented Growth) narratives.

<table>
<tr><th>Scenario</th><th>% share of total household energy use in 2015 (current year)</th><th>Estimated changes in energy use (by fuel) to 2050</th></tr>
<tr><td>SSP1 (Sustainable Growth)</td><td rowspan="3">▪ Electricity: 11% (5 GJ/HH/yr)
▪ LPG: 9% (4 GJ/HH/yr)
▪ Kerosene: 2% (1 GJ/HH/yr)
▪ Charcoal: 46% (21 GJ/HH/yr)
▪ Fuelwood: 32% (16 GJ/HH/yr)</td><td>▪ Electricity accounts for 100% of total household energy by 2050.
▪ Charcoal and wood use phased out by 2030.
▪ LPG and kerosene use peak to 35% and 28% of total household energy in 2030[1], followed by a decline and eventual phase out by 2050.
▪ Total change in energy use (i.e. from phased out charcoal, LPG and kerosene) shifts to electricity.</td></tr>
<tr><td>SSP2 (BAU Growth)</td><td>▪ Electricity accounts for 100% of total household energy by 2050.
▪ Charcoal and wood use halve by 2030 but are entirely phased out by 2050.
▪ Total change in energy use (i.e., from phased out charcoal and wood) shifts to electricity, LPG and kerosene, in equal amounts[2].</td></tr>
<tr><td>SSP3 (Fragmented Growth)</td><td>▪ Electricity accounts for 38% of total household energy by 2050.
▪ Charcoal and wood use halve by 2050.
▪ Change in total energy use (i.e., from reduced charcoal and wood) shifts to electricity, LPG and kerosene, in equal amounts[2].</td></tr>
<tr><td colspan="3">Notes:
[1]The eventual phase out of charcoal in 2030 results in a shift in total energy use towards electricity, LPG and kerosene. This shift is what drives the peak in LPG and kerosene use to 2030. However, with continued urbanization and economic growth in Dar es Salaam, we assume that consumption of these fuels will decline post-2030 with improved electricity access.
[2] The change in total energy use from charcoal and fuelwood use is divided by 3 with amounts (in GJ/HH/yr) transferred to electricity, LPG and kerosene (see Table 2).</td></tr>
</table>

4.3.6. Transport Activities

We project future changes in travel demand based on annual vehicle kilometers travelled (VKT) which accounts for city travel by LDVs and public transit, i.e., dala-dalas, “bajajis” (tricycles), “bodas” (motorcycles) and the BRT. For the baseline, we estimate VKT as a product of the average number of vehicle trips (1.2 trips/person/day (World Bank, 2017a)); average trip distance (20 kilometers (World Bank, 2017a)); mode share; and load factor. Empirical evidence from other developing cities, particularly in Latin America, shows statistically significant correlations between the urban built environment and VKT (Zegras, 2010; Guerra, 2014; Engelfriet and Koomen, 2018). To estimate the correlation between VKT and population density, our modelling draws from research conducted in Mexico City. Using an uncensored latent VKT value that reduces modelling bias associated with different household travel behaviors, a 1% increase in population density is correlated with a 0.03% reduction in VKT (Guerra, 2014). We apply this correlation to our LEAP calculations to estimate the future change in VKT with changes in density for each SSP narrative.

All vehicle load factors and fuel consumption estimates are in Table 2. While, key assumptions for different transport modes include:

- **Electric Vehicles:** We anticipate that some penetration of electric vehicles in Dar es Salaam is likely, given the existing policies and plans to increase production of EVs globally (IEA, 2018). However, it is difficult to make reasonable projections for Dar es Salaam to 2050 given the limited data available on the EV market potential in East Africa. Currently, South Africa is the only African country with electric vehicles, representing only 0.1% of passenger vehicle stock (OECD/IEA, 2017b). Our SSP2 and SSP3 narratives estimate that Dar es Salaam realizes a similar level of EVs in the LDV offleet by 2050 (Table 2); while SSP1 estimates an increase to 1%, similar to levels observed in Europe today (e.g., Netherlands and Sweden) (IEA, 2018). This seemingly low level of EV penetration is consistent with our assumption that these are baseline projections with no special measures taken toward GHG mitigation beyond the broad narrative of each scenario. This assumption is relaxed in our discussion of aggressive

GHG mitigation scenarios in Section 4.4. Finally, we assume electricity consumption of 27 kWh per vehicle-kilometer, consistent with IEA estimates (IEA, 2018).

- **BRT expansion:** For all scenarios, we assume that Dar es Salaam completes Phases 1 to 4 of the BRT by 2050, consistent with current implementation plans (SM.9). Completion of the four phases would result in approximately 900,000 riders per day (World Bank, 2017b), equivalent to 15% of total passenger trips in 2015. Therefore, SSP2 and SSP3 assume that BRT trips increase to 15% (of all passenger trips), while SSP1 assumes a higher increase to 40%, similar to levels reported in Latin American and Chinese cities (UITP, 2015; WRI, 2018). We estimate BRT fuel consumption at 38 liters/100km (DART Agency, 2017) (Table 2), similar to consumption profiles in Latin America and Asian cities, e.g., 33 litres/100km (Jaipur, India) and 40 litres/100km (Quito, Ecuador) (WRI, 2018). We also assume that BRT fuel consumption remains at this level to 2050.
- **Dala-dala travel**: We assume no changes in dala-dala fuel consumption to 2050, i.e. consumption remains at 33 litres/100km (DART Agency, 2017), given the current plans to reduce dala-dala use with a shift to BRT (World Bank, 2017b).
- **LDV travel**: Fuel consumption estimates for the LDV fleet (~12 L/100km) are taken from (World Bank, 2017b). Projecting to 2050, SSP1 envisions that LDV fuel consumption improves to 4.4 L/100km, consistent with IEA targets (IEA, 2017b; OECD/IEA, 2017a). SSP2 and SSP3 assume a less aggressive improvement to 7.4 L/100km, consistent with projections to 2040 for the Africa region (OECD/IEA, 2014).

5. Results and Discussion

5.1. Changes in Dar es Salaam’s total population and density

Across each of the SSPs, Dar es Salaam is shown to experience substantial population growth between 2015 and 2050. Projections for Dar es Salaam’s population to 2050 are based on Equation (3). In all scenarios, Dar es Salaam becomes a megacity by 2050, with the city’s population growing to 16 million under SSP1, 15 million under SSP2 and 12 million under SSP3 (Table 2 and Figure 2). Dar es Salaam experiences the fastest urbanization rate under SSP1, while moderate and slow urbanization occurs under SSP2 and SSP3, respectively. Our SSP1 population projection for 2030 (9.2 million in Dar es Salaam) is within 15% of the United Nation's World Urbanization Projections (WUP) estimate for 2030 (~10.7 million) (UN, 2018). In addition, Hoornweg and Pope (2017) extrapolate the WUP dataset to 2100 and project Dar es Salaam's population at 16 million in 2050. This is consistent with our SSP1 and SSP2 estimates.

Fundamentally, our scenarios are based on Jiang and O'Neill (2017) who project substantial urban growth in Tanzania across each of the SSPs. Estimates to 2050 project up to 60% (SSP1), 50% (SSP2) and 30% (SSP3) urbanization in Tanzania (Jiang and O'Neill, 2017), increasing the urban share of Tanzania's population by 7% to 37% between now and mid-century. Our calculations show that this is equivalent to absolute population increases of 12 million (SSP1), 11 million (SSP2) and 7.5 million (SSP3) between 2015 and 2050 (Figure 2).

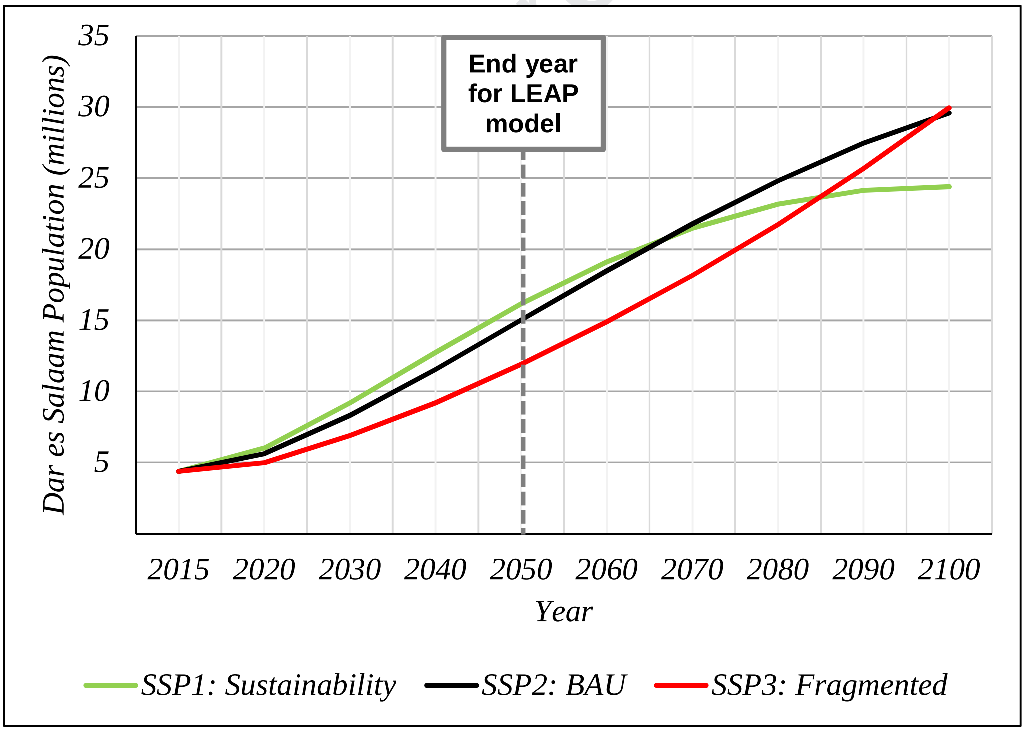

Figure 2: Changes in Dar es Salaam's Population from 2015 to 2050 for SSP1 (Sustainable Growth), SSP2 (BAU Growth) and SSP3 (Fragmented Growth) narratives. Our LEAP model calculates energy use and emissions to the year 2050; though, estimates are extended to 2100 to illustrate the eventual slow-down in Dar es Salaam's population under SSP1. Dar es Salaam's population continues to increase at a higher rate for SSP2 and SSP3.

Dar es Salaam's average population density in 2015 is estimated at 3,100 persons/km^2 (Government of Tanzania, 2014b). By 2050, we estimate that the city's average population density remains the same for SSP1 (3,100 persons/km^2) and increases slightly for SSP2 (3,300 persons/km^2) and SSP3 (3,500 persons/km^2) (Figure 3). Our calculations are based on Jones and O'Neill's (2016) "spatially explicit" global population scenarios, which we use to extract the population density projections for Dar es Salaam (see Methods). Given the counter-intuitive nature of the results – i.e., we would expect higher density under SSP1 would be correlated with sustainable resource use (Kennedy *et al.*, 2015) – we caveat that these projections are the only available dataset estimating future population densities based on the SSPs (Gao, 2017) and estimates can be improved with neighborhood level data collection. The maps (shown in Figure 3) do not illustrate the growth in Dar es Salaam's spatial extent; for example, the likely urban sprawl given the estimated population increases that are projected for each SSP narrative. Therefore, the maps should not be interpreted as accurate projections of density changes of specific neighborhoods. Rather, they provide a baseline assessment of the differences in density change (at the city level) among the three SSP narratives. For example, Figure 3 shows that SSP1 has higher population densities closer to the city centre and along the four major arterial roads (key development areas for the BRT expansion). While settlement patterns for SSP2 and SSP3 are more dispersed – they show higher densities closer to the periphery, particularly in the south-east region of the city. Overall, these patterns can provide insight related to prioritizing policy efforts and infrastructure investments.

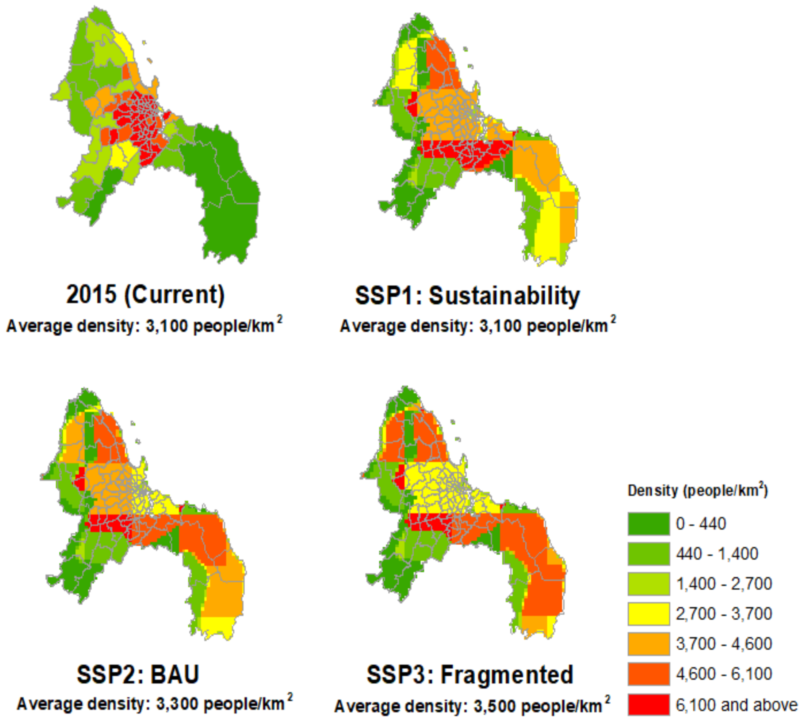

Figure 3: Spatial population projections for Dar es Salaam from 2015 to 2050 for SSP1 (Sustainable Growth), SSP2 (BAU Growth) and SSP3 (Fragmented Growth) narratives.

5.2. Linkages between the SSP narratives and Dar es Salaam's GHG emissions

Across each of the SSP narratives, population growth is a major driver of rising residential energy use and emissions in Dar es Salaam. In 2015, we estimate total emissions from domestic households and transport activities at 1,400 ktCO_2e (Table 4). In 2014, total energy sector emissions in Tanzania were reported at 22.26 MtCO_2e (WRI, 2015). Dar es Salaam accounts for approximately 10% of Tanzania's total population (World Bank, 2018); therefore, we roughly estimate the city's total energy sector emissions at 2,226 ktCO_2e. Emissions from domestic households and road transport count for approximately 80% of national energy sector emissions (Government of Tanzania, 2014a), which would scale to approximately 1,780 ktCO_2e for Dar es Salaam. Therefore, our estimate of 1,400 ktCO_2e for residential sector emissions in 2015 (i.e., resulting from energy uses from domestic household and transport activities) is consistent with the national dataset (within ~18%), as we do not account for energy use in the commercial and industrial sectors.

By 2050, we estimate that Dar es Salaam's total residential emissions will increase to between 25,000 ktCO_2e and 33,000 ktCO_2e (SSP1); 11,000 ktCO_2e and 19,000 ktCO_2e (SSP2); and 5,700 ktCO_2e and 11,000 ktCO_2e (SSP3). This is correlated with an increase in per capita emissions from 0.2 tCO_2e in 2015 to between 1.5 tCO_2e and 2 tCO_2e (SSP1); 0.7 tCO_2e and1.3 tCO_2e (SSP2); and 0.4 tCO_2e and 0.9 tCO_2e (SSP3). Our estimates represent a 4 to 24-fold increase in emissions to 2050 (relative to 2015), due to the higher urban population in 2050 and increased energy access and electricity consumption. Increased emissions from household electricity use are due to the assumed continued use of fossil fuels for electricity production, consistent with projections under Tanzania's national power plan (Government of Tanzania, 2016a). The Tanzanian government projects that natural gas and coal will continue to dominate Tanzania's electricity mix to 2040, accounting for 40% and 30%-35%, respectively of the mix (Government of Tanzania, 2016a). We apply these projections across each of our scenarios (see SM.3.).

To our knowledge, there are no other projections of residential GHG emissions in individual SSA cities against which to compare our results. However, a growing number of regional studies indicate an overall upward trend in GHG emissions due to increased electricity access and economic activity in the region. For example, Calvin *et al.* (2016) estimate that GHG emissions in the SSA region will increase by 2.7 % to 3.8% per year from 2005 to 2100 (or by ~122% to ~171% by 2050). The International Energy Agency (IEA) projects slightly lower levels of growth, estimating an ~ 80% increase in GHG emissions in the SSA region by 2040 (i.e., from 1,141 Mt CO_2 to 2,051 Mt CO_2 in 2040) under their "Current Policies" scenario (IEA, 2017b). While, van der Zwaan *et al.* (2018) estimate a 100% (2-fold) increase in GHG emissions in continental Africa (including North Africa) from 2015 to 2050 under their "reference scenario", and a 30% to 40% increase by assuming (1) a 4% annual increase in the CO_2 price ("TAX" scenario) or (2) a 20% reduction in global emissions by 2050 ("CAP" scenario). In contrast, the results presented in this paper are applicable to the city rather than the regional level (as the above-mentioned regional studies combine both rural and urban data). This partially explains the variation in results, and our substantially higher estimates, given the larger concentration of energy use in cities. Moreover, our emissions scenarios are presented as a range, based on assumptions of household size, with the upper estimate reflecting the lower household size assumption (given that total household energy use is kept constant – see Methods).

5.2.1. Household Emissions

Between 80% and 90% of total residential emissions are due to household electricity use (given that 70% – 75% of the electricity mix is from natural gas and coal to 2050 (SM.3)). The increasing number of households – particularly under SSP1 – is what fundamentally drives emissions from electricity production (assuming that total household energy use remains constant to 2050). Table 2 shows that electrifying all households under SSP1 and SSP2 narratives will be equivalent to electrifying an additional 3 to 11 million households in 2050 (from 1.3 million households in 2015). Moreover, the GHG intensity of electricity generation remains high even under SSP1 (remaining at ~405 gCO_2e/kWh in 2050) (Table 2) – a level that well exceeds the IEA target of 254 gCO_2e/kWh by 2060 (IEA, 2017a). Given that the narratives defined in this paper do not assume aggressive GHG mitigation policies – and instead, offer baseline trajectories to 2050 – we find that the highest GHG emissions are associated with SSP1. Therefore, our findings highlight the opportunity for more aggressive GHG mitigation policies to reduce the GHG intensity of electricity generation (such as integrating renewable sources) to offset future residential emissions increases in Dar es Salaam.

The fact that an SSP3 trajectory results in the lowest residential emissions is largely due to the inequalities in access that are reinforced under this scenario (i.e., no changes in electrification from 2015) and a 25% lower population under SSP3, compared to SSP1. Under SSP1 and SSP2, Dar es Salaam will likely surpass in absolute terms, in 2050, the current (2013 – 2015) GHG emission levels of North American and European cities (C40 Cities, 2017) (SM.5). On a per capita basis, we find that emissions remain low compared to other global cities, assuming that total household energy use remains constant. For example, per capita emissions (from buildings and transportation) in cities such as New York, San Francisco or London (where data is more robust) were estimated at 5.7 tCO_2e/capita (in 2014), 5.5 tCO_2e/capita (in 2015), and 4.5 tCO_2e/capita (in 2013) (C40 Cities, 2017) (SM.5), compared with only 0.5 tCO_2e/capita to 2 tCO_2e/capita across our scenarios.

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Finally, we do not account for biogenic carbon emissions from charcoal or wood burning but illustrate biogenic emissions for each scenario in SM.7, which increase to ~2,500 ktCO_2e – 5,000 ktCO_2e under SSP3 (which assumes a continued reliance on charcoal to 2050). Ultimately, increasing charcoal use under SSP3 may threaten forests in Dar es Salaam's surrounding rural areas, given that the city already consumes nearly 70% of all charcoal produced in Tanzania, which threatens an estimated 2.8 million hectares of forests (~8.5% of Tanzania's total forest cover) (Msuya *et al.*, 2011). The use of charcoal and fuelwood is also linked to premature mortality and morbidity from indoor air pollution (WHO, 2012). Globally, the World Health Organization (WHO) estimates that over four million premature deaths were attributed to household air pollution from the traditional use of biomass fuels for daily cooking activities in 2012 (WHO, 2012).

5.2.2. Transport Emissions

Road transport is a smaller driver of total residential emissions compared to household emissions. Overall, total emissions from transport increase from 490 ktCO_2e (in 2015) to 600 ktCO_2e (SSP1); 900 ktCO_2e (SSP2); and 700 ktCO_2e (SSP3) in 2050 (Table 4). We find that annual VKT per capita does not change substantially across any of the narratives (Table 2), with the highest drop (only ~3%) in VKT per capita, projected under SSP3, which is due to the slightly higher population density assumed under this narrative. In addition, although population increases by three to four times by 2050, transportation emissions in all scenarios increase much more slowly. This is due primarily to improving fuel economy and changes in mode share (responsible for a 20% - 60% drop in per capita transportation emissions relative to 2015). Across all scenarios, emissions from LDV travel (with minimal ridesharing) dominate; accounting for over 80% of transport emissions (Table 4).

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Table 4: Total residential emissions from household and transport activities in Dar es Salaam by activity. Results for SSP1 (Sustainable Growth), SSP2 (BAU Growth) and SSP3 (Fragmented Growth) narratives for 2030 and 2050.

		Current year – 2015	SSP1 – 2030	SSP2 – 2030	SSP3 – 2030	SSP1 – 2050	SSP2 – 2050	SSP3 – 2050
HOUSEHOLDS								
▪ **Electricity use**	$ktCO_2e$	700	[6,400 - 7,100][1]	[3,200 - 4,100]	[1,900 – 2,400]	[24,000 – 32,000]	[9,000 – 17,000]	[4,500 – 8,900]
▪ **LPG use**		60	[300 – 390]	[230 – 290]	[130 – 170]	-	[700 – 1,300]	[330 – 650]
▪ **Kerosene use**		10	[170 – 210]	[110 – 140]	[50 – 60]	-	[400 – 700]	[200 – 300]
▪ **Charcoal use[2]**		120	-	[90 – 120]	[80 – 140]	-	-	[130 – 260]
▪ **Wood use[2]**		20	20	20	20	-	-	[20 – 50]
TOTAL EMISSIONS (HOUSEHOLDS)	**$ktCO_2e$**	**910**	**[6,700 - 7,500]**	**[3,700 – 4,700]**	**[2,200 - 2,800]**	**[24,000 - 32,000]**	**[10,000 - 18,000]**	**[5,000 - 10,000]**
ROAD TRANSPORT								
▪ **LDV use**	$ktCO_2e$	440	560	600	500	500	800	600
▪ **Dala-dala use**		20	40	40	30	50	60	40
▪ **Bajaji or Boda use**		30	50	40	40	80	80	50
▪ **BRT use**		-	0.4	0.2	0.1	2.0	0.7	0.3
TOTAL EMISSIONS (ROAD TRANSPORT)	**$ktCO_2e$**	**490**	**700**	**700**	**600**	**600**	**900**	**700**
TOTAL (RESIDENTIAL EMISSIONS)	**$ktCO_2e$**	**1,400**	**[7,400 – 8,200]**	**[4,400 – 5,400]**	**[2,800 – 3,400]**	**[25,000 – 33,000]**	**[11,000 – 19,000]**	**[5,700 – 11,000]**
	tCO_2e/capita	**0.2**	**[0.8 – 0.9]**	**[0.5 – 0.6]**	**[0.4 – 0.5]**	**[1.5 – 2]**	**[0.7 – 1.3]**	**[0.5 – 0.9]**
	[% change in total residential emissions]		*[430% – 500%]*	*[210% – 290%]*	*[100% – 140%]*	*[1700% – 2300%]*	*[690% - 1300%]*	*[310% -660%]*

Note:
[1]Variation in GHG emissions due to variation in household size for each SSP narrative. See Table 2.
[2]LEAP model does not account for carbon-dioxide emissions from charcoal and wood use (biogenic CO_2). See SM.7. for estimates of biogenic CO_2 emissions.

▪ Values rounded to 2 significant figures. Values do not represent the precision of the estimates in the LEAP model.

- Totals do not add due to rounding.
- Refer to SM.2 for emissions factors for all fuels used in the LEAP model.

5.3.Correlation between total residential emissions, GDP and population

By plotting population and total residential emissions on a logarithmic scale, we find that population is positively and linearly correlated with GHG emissions. The resulting elasticities reveal an increasing and positive relationship for all SSPs. For example, our findings show a 1% increase in total population is correlated with a 2.2% to 2.4% increase in total residential emissions for SSP1, compared to an increase of 1.7% to 2.1% for SSP2 and 1.5% to 2.2% for SSP3. Dar es Salaam's population growth is projected to result in a super-linear scaling relationship for all SSP narratives, with emissions growing at 150% to 240% faster rates than population to 2050. While some studies have shown a linear (Fragkias *et al.*, 2013) and sub-linear (Kennedy *et al.*, 2015) scaling relationship between city population and emissions, these correlations have been weakest in low-GDP cities (including African cities) given their low levels of access to basic infrastructure services such as electricity (Kennedy *et al.*, 2015).

Urban growth in low-GDP cities such as Dar es Salaam requires that resource use increases to a threshold that supports sustainable living standards for residents. Our results show that emissions in Dar es Salaam increase super-linearly due to improved energy access and electricity-use, and the likely high GHG-intensity of new electricity sources to 2050 (Table 2). Furthermore, our findings are influenced by the potential drop in household size and assumption that traditional sources being phased out (wood and charcoal) would result in low emissions reductions due to the exclusion of biogenic CO_2 emissions from the emissions accounting.

SSP1 is associated with the highest level of economic growth (IIASA, 2015). Projections show that Tanzania is expected to experience a nearly eight-fold increase in GDP under SSP1, from USD 49 billion in 2015 to USD 400 billion in 2050, while under SSP2 and SSP3, GDP is expected to increase to USD 260 billion and USD 177 billion, respectively. These estimates are available in the SSP database (IIASA, 2015). Therefore, plotting Dar es Salaam's annual residential emissions per capita against the projected GDP per capita (using a logarithmic scale) reveals a weak (sub-linear) correlation between GDP and emissions. For example, a 1% increase in GDP per capita is correlated with an increase of 0.07% to 0.1% for SSP1 and SSP2, and 0% to

0.1% for SSP3 (SM.6). As our model does not explicitly account for the likely rise in demand for household energy services and transportation in response to growing GDP, these correlations are (a) likely underestimated, and (b) not explicitly causal (though potentially linked via the SSP narratives).

5.4. Comparison of Dar es Salaam's emissions projections with those of other Global South cities

A limited number of studies project changes in residential GHG emissions in individual SSA cities, or at the regional level. The studies reveal an overall increasing trend in GHG emissions, though at much lower rates than projected in our paper. Like the current study, some of the studies find that electricity-based emissions play a dominant role in emissions increases (Table 5). However, accounting methods vary among the studies, where electricity emissions are calculated separately or included within a larger energy sector. For example, in their "BASE" scenario, Senatla (2011) show that electricity generation contributes more than 95% of Gauteng's residential sector GHG emissions between 2007 and 2030. Regional projections by Stone and Wiswedel (2018) estimate a 240% increase in total urban emissions between 2012 and 2040, with transport and industry (including electricity use from industry) being the largest contributors. Similarly, studies in other regions of the Global South (i.e., Asia and Latin America) show that transportation and industry drive GHG emissions given their more advanced levels of socio-economic development. Table 5 compares our results with those of other studies in the literature to (1) demonstrate the large difference between our results and example results from other regions, and (2) further illustrate the need for additional GHG emissions studies in large SSA cities such as Dar es Salaam.

Table 5: Comparative GHG emissions results and main drivers of GHG emissions for selected cities or regions in the Global South

Study	*City/Region*	*Scope*	*Projection timeline*	*Percentage change in GHG emissions from starting year*	*Main driver of GHG emissions*

This paper	Da es Salaam, Tanzania	Residential sector	2015 – 2050	310% - 2300%	Electricity *(Electricity use increases from 5GJ/HH/yr in 2015 to 18 – 46GJ/HH/yr in 2050 – see Table 2)*
(Senatla, 2011)	Gauteng, South Africa	Residential sector	2007 – 2030	~100%[1]	Electricity
(Stone and Wiswedel, 2018)	SSA region	Total urban emissions[2]	2012 - 2040	240%[1]	Transport and Industry
(Godfrey and Xiao, 2015)	SSA region	Total urban emissions[2]	2012 – 2030	61%[1]	Variable based on city income categorization (i.e., middle-income or least developed city)
(Collaço *et al.*, 2019)	São Paulo, Brazil	Total urban emissions[2]	2014 – 2030	43%	Transport
(Huang *et al.*, 2019)	Guangzhou, China	Total urban emissions[2]	2010 – 2030	~20%	Industry and Transport

[1]Projections are based on business-as-usual or baseline scenarios mentioned in each study.

[2]Total urban emissions refer to emissions in all urban sectors, including industrial, commercial, residential and transportation. Though, studies may use other categories in their accounting approach.

5.5. Implementing aggressive GHG mitigation policies under SSP1

Of all regions in Africa, East Africa has the highest renewable energy potential (Lucas *et al.*, 2017). Estimates project that Tanzania can realize the following grid mix under an SSP1 narrative by 2040: 12% hydropower, 30% solar, 20% wind, and 14% geothermal (leaving 23% for natural gas and coal combined) (Lucas *et al.*, 2017). These estimates are consistent with regional models for electricity generation in East Africa and reflect the more rapid development of renewables (wind and solar) in rural areas. The different electricity generation scenarios are detailed in SM.3. We include an additional narrative (based on SSP1 data and assumptions; see Table 2) to test the impact of aggressive decarbonization of electricity, combined with low-GHG investments in transportation. Actions examined are as follows:

(1) 70% of the electricity generation to be from solar, wind and geothermal sources by 2050 (Lucas *et al.*, 2017).

(2) The BRT system carries ~50% of all passenger trips.

(3) 60% of the LDV fleet is electrified by 2050, consistent with global trends (IEA, 2017a).

As shown in SM.4, generating 70% of electricity from renewable sources in 2050 would reduce the GHG intensity of the grid to ~129 gCO_2e/kWh, compared to 405 gCO_2e/kWh under SSP1 (Table 2). By 2050, total residential emissions would increase to 7,400 $ktCO_2e$ – 11,000 $ktCO_2e$, which is ~66% lower than under our original sustainability narrative (SSP1), though still far higher than current (2015) emissions. Total residential emissions for this aggressive GHG mitigation narrative, are compared with those of the other SSP narratives in SM.8.

6. Research limitations and areas of future work

There are important areas of future work that are not explicitly considered in our modelling. First, the assumption that household energy use remains constant is an important limitation. This assumption is expected to underestimate demand for energy in a developing economy such as Dar es Salaam. Thus, our scenarios are likely conservative, even though they show an order of magnitude increase in GHG emissions by 2050 (ranging from 4 to 24 times the 2015 level, as detailed in the results and conclusions). Second, if vehicle manufacturers fulfill commitments to scale up production of EVs or hydrogen fuel cell vehicles in the coming decades (IEA, 2018), and these become more broadly affordable, Tanzania may see growth in EVs by 2050 beyond the estimates projected in our model (see Table 2). Also, improvements in road infrastructure and public transit (with the BRT expansion) may result in induced or latent travel demand similar to trends observed in European and North American cities (Cervero, 2002; Noland and Lem, 2002), which will impact transport-related emissions. Third, our estimates exclude Scope 3 or upstream emissions from infrastructure supply chains, which could also contribute substantially to projected GHG emissions. For example, research conducted in Delhi, India estimated that up to 32% of the city's emissions was due to out-of-boundary (Scope 3) activities such as fuel processing, air travel, cement use, and food production (Chavez *et al.*, 2012). Fourth, biogenic emissions from charcoal use are considered as carbon neutral, consistent with IPCC guidelines. However, biogenic emissions would nearly double (assuming HH size reduces to two persons per household by 2050) under SSP3 (SM.7), influencing land degradation and public health outcomes (due to indoor air pollution). Finally, as noted in our introduction and methods, future work could also incorporate emissions from other sectors, especially industry, which are expected to contribute substantially to future energy demand in the SSA region (IEA, 2019).

7. Conclusions and implications for energy policy

In this paper, we:

- Provide the first projection of residential energy use and GHG emissions in Dar es Salaam and demonstrate the use of the SSPs at the city scale.
- Analyze the key drivers of residential energy use and GHG emissions in a large SSA city, Dar es Salaam, offering new insights for the region.
- Demonstrate a method for projecting emissions in a data-poor environment.
- Show the wide uncertainty in these future projections, while also demonstrating the order of magnitude jump in emissions that can be expected in Dar es Salaam to 2050.

Key results are summarized as follows:

- **Dar es Salaam is projected to experience a 4- to 24-fold increase in residential GHG emissions by 2050**. Though Dar es Salaam's current (2015) emissions of 1,400 ktCO_2e (~ 0.2 tCO_2e/capita) are low compared to the emissions of other global cities (see SM.5), emissions are expected to increase to between 5,700 ktCO_2e (~ 0.5 tCO_2e/capita) and 33,000 ktCO_2e (~ 2 tCO_2e/capita by 2050. The upper estimate is as high as the recorded emissions of Global North cities such as New York, San Francisco and London, among others.

- **Electricity access is the largest driver of residential emissions to 2050.** Assuming that total household energy use remains constant to 2050, with the relative shares of fuel use changing for each SSP narrative (Table 3), we estimate that GHG emissions from electricity production (due to improved electrification and access to services) will be a major driver of future residential emissions in Dar es Salaam, i.e., accounting for between 80% and 90% of total residential emissions. This is largely due to continued reliance on fossil fuels for electricity generation. Even under SSP1 (the sustainability scenario), we project that fossil fuels will account for a dominant portion of Tanzania's electricity mix, i.e., 40% and 30% from natural gas and coal, respectively, compared to 20% and 10% from hydro and other renewables (i.e., wind and solar) (SM.3).
- **Across all scenarios, Dar es Salaam's residential emissions increase super-linearly with population size, mainly due to household electricity use**. The high GHG intensity of electricity – which remains at 405 gCO_2e/kWh for SSP1 and SSP2 – results in a 6- to 35-fold increase in household emissions relative to 2015.
- **The sustainability scenario (SSP1) has the highest residential emissions due to increased household and transportation energy services**. This suggests a particularly acute need to promote low-GHG development in Dar es Salaam to reduce any tension between social and environmental goals.
- **Dar es Salaam's current low emissions provides an opportunity to design a low-GHG future. This will hinge on the implementation of low-GHG investments (namely, the decarbonization of electricity production) during these next stages of urban growth.** As shown in our aggressive GHG mitigation scenario (Section 4.4), decarbonizing Tanzania's electricity grid through the use of renewable energy sources such as solar, wind and geothermal could reduce the city's total residential emissions by up to 66% by 2050 (SSP1). However, realizing this pathway will hinge on the

development of urban policies and financing for aggressive GHG mitigation during these next stages of urban growth.

Lastly, though not explicitly explored in this paper, realizing a low-GHG transition in Dar es Salaam requires the consideration of the city's broader socio-economic development goals. Policies need to leverage synergies between energy sector investments, i.e., financing to decarbonize electricity with renewable technologies or scale-up public transport with the BRT network, and socio-economic development objectives at the city and national level. For example, given that Dar es Salaam is growing amidst other socio-economic challenges, including urban inequality, poverty and climate change, policy actions would require cross-sectoral collaboration between key stakeholders, government agencies, infrastructure service providers and the private sector to identify co-benefits between low-GHG investments and priorities in key sectors. This will be critical for ensuring that low-GHG investments improve the living standards of marginalized groups and that they benefit from the transition.

Declaration of competing interest

None.

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Modelling future patterns of urbanization, residential energy use and greenhouse gas emissions in Dar es Salaam with the Shared Socio-Economic Pathways

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HIGHLIGHTS

This paper:

- Provides the first projection of residential energy use and GHG emissions in Dar es Salaam and demonstrate the use of the SSPs at the city scale.
- Analyzes the key drivers of residential energy use and GHG emissions in a large SSA city, Dar es Salaam, offering new insights for the region.
- Demonstrates a method for projecting emissions in a data-poor environment.
- Shows the wide uncertainty in these future projections, while also demonstrating the order of magnitude jump in emissions that can be expected in Dar es Salaam to 2050.

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: